



Self-Ligation *in* Orthodontics

THEODORE ELIADES
NIKOLAOS PANDIS

FOREWORDS BY
LYSLE E. JOHNSTON, JR
& LARRY W. WHITE

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Self-Ligation in Orthodontics

An evidence-based approach to biomechanics
and treatment

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and

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Foreword

It may seem strange for a retired academic to comment on a book that in the last analysis deals with brackets and archwires. I disagree. It has been said that all fashion tends to end in excess; the wild, seemingly unprofessional claims surrounding self-ligation and the extent to which they are tolerated constitute a dangerous example. As I see it, events have progressed to a point where the specialty has to take a stand if it is to maintain its status as a learned calling. There is more at stake than market share.

A century ago, the ‘fathers of orthodontics’ accepted – almost as an article of faith – the proposition that the specialty must, of necessity, be grounded in the precepts of science. Over the years, however, we have seen a gradual erosion of our respect for this basic principle. One need look no further than the controversy surrounding ‘evidence-based orthodontics’ to appreciate the extent to which the specialty tends to see ‘science’ as an irrelevant impediment to the orderly flow of commerce. The realization that a practice can be prosecuted more or less in a scientific vacuum has fostered a *laissez-faire* approach to practice – you do it your way, I’ll do it mine. Everything works well enough to pay the bills; nobody dies from anchorage loss.

Given that there are few accepted standards of practice, many look more to industry rather than to academia for guidance. In the end, however, a company’s fiduciary responsibility is to its stockholders, not to us. Given that the companies supply us with high-quality, salable commodities and underwrite many of the speakers at our meetings and continuing education programs, it is convenient to ignore this probable conflict of interests. It is a Faustian bargain in which the specialty seeks to retain its soul by the simple expedient of adding asterisks to our meeting programs. In the process, we have become inured to

the hyperbole of commerce: we are used to being told that a given bracket–archwire combination is more convenient, faster, less painful, etc. Live and let live; however, when the claims go so far beyond the expected degree of exaggeration that they begin to distort the clinical marketplace, clinicians begin to grumble. ‘Somebody ought to do something!’ Unfortunately, we are the ‘someone’. Ultimately, our specialty will be known by our collective response to this challenge.

Historically, orthodontists have been guided by a few core assumptions: expansion won’t hold; lower incisors should be upright over basal bone; in the battle between bone and muscle, muscle will win, etc. In contemporary orthodontics, however, the number of undisputed ‘laws’ has dwindled to perhaps just one: bone doesn’t expand interstitially; it can only remodel on a surface. Accordingly, any claim that a given bracket–archwire can grow bone invokes an effect that not only is assumed to be impossible, but also one for which there is no convincing theoretical basis. We have seen it all before. Some 80 years ago, the Johnson ‘twin-arch automatic’ was a revelation. Compared to contemporary appliances, twin-wire was almost magic in the way its ligatureless, low-friction brackets, and light archwires could resolve incisor irregularity. Unfortunately, this ‘automatic’ appliance had trouble with extraction and – not unexpectedly – proved unable to grow bone. Although it required no wire-bending and could support a practice, it was incapable of many things that orthodontists thought were important. In those simpler times it didn’t dawn on anyone to claim that the appliance could grow bone or modify the envelope of motion of the lips, cheeks, and tongue. Instead, the specialty moved on to more capable, albeit technically demanding, appliances. In contrast to the Johnson twin-wire, contemporary self-ligating

appliances probably have no inherent technical weaknesses that would preclude their use in the full range of malocclusions, both extraction and non-extraction. In the end, their major weakness seems to be the miasma of unsubstantiated marketing claims that serve to confuse the practitioner and debase the specialty.

If an appliance can't grow bone, its use by a given office to treat everything 'non-extraction' will be a disservice to the protrusive, crowded patient who has been unlucky enough to present there for treatment. Alternatively, if an appliance, against all odds, really can speak the language of the osteoblast and

osteoclast, wild claims deflect attention and delay acceptance. Either way, the specialty has reached a critical intellectual juncture. Extraordinary claims require extraordinary proof.

This book is a start.

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Foreword

No orthodontic development since the advent of the Straight Wire Appliance™ (SWA) in the 1970s has animated and excited the profession quite as much as the re-emergence of self-ligation brackets in these early years of the twenty-first century. The idea of self-ligation brackets has intrigued and fascinated orthodontists since the time of E. Angle, and some of his patented iterations of the edgewise bracket show this preoccupation with simple ligation of the archwire.

Several of Angle's successors such as McCoy, Boyd, Ford, Russell and others continued the quest for more efficient and uncomplicated methods of ligation. However, a confluence of factors interrupted this pursuit in the late 1930s, e.g. Tweed's new diagnostic and treatment regimens along with World War II seemed to have erased any general interest in the self-ligation concept, although the snap channel bracket from Rocky Mountain Orthodontics still claimed a few disciples.

Serious efforts to re-establish self-ligation brackets started again in the 1970s with the SPEED bracket developed by Herb Hanson and the Ormco's Edgelock championed by Jim Wildman. Unfortunately, these two new varieties of self-ligation brackets fell victims to the surge of interest created by the SWA along with some of their own design deficiencies.

Within the past few years, clinicians worldwide have shown some spectacular therapies using the newest self-ligation brackets. But with all of the interest, conferences and investment in this concept, most of the publications regarding the various bracket designs and techniques remain decidedly anecdotal. An embarrassing scarcity of objective literature exists regarding the self-ligation bracket experience and this new publication seeks to remedy the glaring lack of evidence with a fair, non-prejudicial and enlightening consideration of the complete topic. Aside from presenting the fascinating history and evolution of modern self-ligation brackets,

the authors, along with esteemed and knowledgeable colleagues, have meticulously examined the common claims of clinicians and manufacturers regarding features of these new brackets such as their efficiency and treatment outcomes, root resorption effects, periodontal consequences, oral microbiota changes and treatment biomechanics.

Lest readers think this volume reduces self-ligation brackets to nothing more than laboratory measurements, graphs and statistics, Drs Eliades and Pandis have also included enough therapies by well known and respected clinicians skilled and experienced with self-ligation brackets to satisfy the most clinically oriented orthodontists. The gap between knowledge by description and knowledge by acquaintance is wide and sometimes seemingly unbridgeable, but these authors have done a masterful job of filling the fissure between research and clinical experience and shown how these two disciplines can reinforce one another and strengthen the commitment to professional excellence.

Clinicians and researchers anxious to review an impartial and comprehensive collection of data regarding self-ligation brackets will find no better source than this new publication devoted solely to the subject. Neither will they discover more disciplined researchers upon whom they can depend for accuracy and integrity than Drs Eliades and Pandis. They have provided the profession with the definitive text on self-ligation brackets, and orthodontists along with their patients will benefit greatly from their efforts.

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Preface

Although the concept of self-ligation was introduced in orthodontics several decades ago, it was only in the last 15 years that these appliances became available in their current form. Marketing of self-ligating brackets has shown a peak during the past few years with every major orthodontic materials manufacturer introducing a self-ligating bracket in the market of either active or passive self-ligating mode.

It may be interesting to view the evolution of the self-ligating concept from the perspective of the Gartner's hype cycle¹, which was introduced in 1995 to describe the progressive stages of a new technology from its conception to its adoption by the market. This cycle is depicted by a characteristic curve consisting of an initial sharp rise and a subsequent rapid drop, followed by a plateau, and applies to both, emerging technologies, new products or techniques. The cycle progresses through the following stages:

1. 'Technology trigger', when the technology is first introduced
2. 'Peak of inflated expectations', the first peak after the technology has been introduced without substantiated information
3. 'Trough of disillusionment', when the technology does not meet expectations, disappoints, and to a large degree is abandoned
4. 'Slope of enlightenment' when even though the technology has been largely abandoned, some individuals still use it and experiment with it in order to understand its benefits
5. 'Plateau of productivity' when the benefits of the technology are evident and its performance becomes consistent

A similar hype cycle appears to be occurring in the field of self-ligating appliances; we are probably at

the early stages of the cycle, at which products and their benefits are over hyped with limited or no substantiation. This is implied by the fact that the high appeal of self-ligating brackets to clinicians and resultant increased interest of manufacturers was not followed by an analogous clinical substantiation.

With the exception of a handful of retrospective studies on SPEED brackets, for more than 15 years, the sole clinical evidence on the efficiency of these appliances was confined to clinical observations, opinion articles and case reports. Informative as they might be, these sources are often misleading because they are based on a subjective view, and are prone to prejudice in the selection of participants, outcome bias and coincidental correlation. *Post hoc ergo propter hoc*, i.e. 'after this, therefore, because of this', refers to the fallacy of assigning a causal relationship to a variable for an outcome, just because the former happens to chronologically precede the latter².

In the absence of appropriate research policies, the presence of conflict between the user-author and the industry may further complicate the extrapolation of conclusions from studies. Recent reports have noted that such a conflict represents a major issue in medical research, with almost 15% of the publications reporting absence of conflict, evidently proven to be associated with the pharmaceutical industry³. Because the disclosure of interest was not found to be taken seriously by the readers, major biomedical periodicals have adopted a policy which excludes all publications reporting conflict⁴. Apart from the abovementioned considerations, classes of publications such as opinion articles and case reports are at the lower level of hierarchy of evidence and can only serve as stimulating factors for further

research, whereas no actual assessment of the performance of the material is furnished.

The lack of rigid evidence on the subject, which has prevailed for over a decade after the introduction of self-ligating brackets, is largely due to the unique mode of introduction of new materials in orthodontics. The situation seen in our field resembles that seen in cosmetic rather than biomedical products, since no proof is required to support the claims made by the manufacturer about the advertised 'special' feature of the product. This leads to a poor substantiation of the marketed action, which is in striking contrast to broader applications of biomedical materials such as coronary stents or orthopedic prostheses.

To respond to scientific scrutiny, the industry, through a dense network of speakers and self-organized conferences, pushes an agenda, which in principle can be summarized in the following dogma: *'proposals on the conjectural mechanism of action of an appliance may not require substantiation if there is no evidence to contradict it'*. To bring things back on track, it must be emphasized, that, as in all scientific adventures, the burden of verifying a hypothesis lies on the side which proposed it in the first place; it follows that the lack of evidence rejecting an argument does not verify its validity.

The tactic presented in the previous paragraph has resulted in statements and claims which contradict fundamental principles of mechanics and craniofacial biology, actually doing injustice to a bright idea for a new appliance. This is because the favorable features of the new product are exaggeratedly stretched to take the position of a new theory of tooth movement, when the innovation is limited to modifying the design of the engagement mode of the bracket. It must also be remembered that the periodontal ligament of our patients' teeth cannot differentiate between forces applied by self-ligating or conventional brackets, finger pressure, or toothpicks. It can only sense changes in direction, magnitude and duration, and currently, very little is known on the effect of a wide range of magnitude and duration within the physiological range, on tissue response.

To avoid potential undesirable sequelae, a body of applied and clinical evidence is necessary to substantiate the application of new materials and techniques. Specifically, there has been a need to introduce a source of fundamental principles governing self-ligation, to describe their properties from a materials science, biomechanics and clinical orthodontic per-

spective, and to critically review the evidence available on their performance. This will assist the clinician in defining the actual advantage and indications of self-ligation.

HOW TO READ THE BOOK

The basic scope of this book is to comprehensively review self-ligation and summarize the evidence available in the literature. Each chapter addresses a specific question pertinent to the properties, basic and clinical performance of self-ligating brackets, including: force and moment application; temporal variation of force in active self-ligating brackets; periodontal considerations and oral microbiota alterations; root resorption; biomechanics; and treatment efficiency and associated dental effects.

The text is written in a manner which addresses issues, often basic in character, from the perspective of a clinician. In areas requiring background knowledge such as biomechanics (based on mechanics and materials science), clinical research (related to epidemiology), tooth movement (dealing with molecular biology) and oral flora changes (discussed from a microbiological view), background texts written by eminent scholars provide the essentials of the corresponding disciplines to facilitate an insight into the topic.

Apart from the appraisal of the currently available evidence, the book also contains clinical therapeutic guidelines and suggestions, which are the result of the accumulated experience of prominent clinicians. Although the reader may be puzzled by the occasional contradiction between the information and the evidence presented in other chapters, the clinical wealth of the content of these chapters should not be overlooked, since a variety of views can only widen the perspectives of practising orthodontists.

The team of contributors to this book, spanning over eight countries on three continents, comprises the most active group of individuals in basic and clinical research on self-ligation. A substantial portion of the clinical investigations on the subject has been generated by the efforts of chapter authors; we, therefore, gratefully acknowledge their willingness to share their expertise with the readers.

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Acknowledgments

This book was conceived during the period one of us (TE) was tenured at the Aristotle University of Thessaloniki (AUTH), Greece; the content of this text was structured based largely on the material covering the graduate seminars given primarily to AUTH and to a lesser degree to the University of Athens and a number of European Universities. The collaboration of many colleagues, who provided the opportunity for this interaction, by integrating TE's orthodontic materials seminars into short-term or formal post-graduate *curricula*, is greatly appreciated. The list includes Professors Andreas Jäger and Christoph Bourauel at Bonn, Germany; Stavros Kiliaridis at Geneva, Switzerland; Kevin O'Brien and David C. Watts at Manchester, UK; Anne-Marie

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Dedication

In loving memory of Constantinos

T.E.

'We are afflicted in every way but not crushed; perplexed but not driven to despair'

2 Corinthians 4:8

To Brandi and Emily for their love, support, and patience

N.P.

Introduction

Development of Light Force Orthodontics: The Original Pin-a-Slot Appliance as Ancestor to Modern Brackets

Jeffrey S. Thompson and William J. Thompson

INTRODUCTION

In these days of multifaceted versatile brackets with self-ligating systems of all sorts, it is often forgotten that the concept of light forces and large inter-bracket distances being used as a mechanical advantage, has been around for many years. We seemed to have given in to the esthetic components at the sacrifice of biomechanics. Yes, we have ingeniously designed a plethora of miniature caps, locks, snaps and slides to maintain the archwire in the bracket slot. There is from this singular ligation an intrinsic ability to reduce the wire insertion time, but we must consider the biomechanical ramifications and engineering limitations of the seemingly ‘all or nothing’ activation. The resultant tendency is to compensate for this activation through the use of alternative archwire compositions, hence the need for braided, nickel–titanium and heat-activated wires. Many of these new self-ligating systems must include a reduction of common variability of forces, which are typically at the disposal of routine edgewise brackets, i.e. steel ties, elastic ties, wedges, pins, threads or modules.

Another consideration is how does the orthodontist then manage anchorage? Do we rely on additional extraoral contraptions, intraoral devices or even removable appliances? How is static versus dynamic anchorage incorporated into the treatment design? Is it an extraction vs non-extraction space management decision? Are elastics, titanium springs,

closing loops or temporary anchorage devices (TADs) required to a greater extent at the expense of the bracket systems? All these decisions are operator determined and vary as to the training and experience of the operator.

In this brief introductory text we will review a few of the many systems that have led us into the self-ligating frenzy, recalling how similar the biomechanical requirements and challenges are. As we look back we observe a cyclical nature of techniques and mechanics fluctuating between rigid force systems, functional appliance concepts, extraoral avenues and light wire forces. It is the light wire, segmental mechanic systems that have been available throughout the literature for years, which shows us time repeats itself in only slightly different form.

PIN-A-SLOT APPLIANCES

Mechanical and ligation challenges have been around since E. Angle’s era. Removable appliances, Crozats, Hawleys and very sophisticatedly designed cast appliances were present early in our development. This was followed by our early desire to invent some type of predesigned orthodontic system. Nearly every dental and skeletal dimension possible was calculated, analysed and compared, then put to the test in the form of a new bracket design or mechanical system. Orthodontists selected presized, prefrit,

prebent and even attempted to predict or predetermine the dental and facial objectives after analysis of the increasingly accurate and sophisticated records. Combining orthodontic mechanics is not a new concept, but is the fastest growing form of treatment.

The formation of an efficient light wire force system came into vogue in the 1950s. It is interesting to note the similarities in bracket size and inter-bracket distance, then and now. Orthodontists leaned heavily on clinicians like A. Chug Hoon, M. Fogel, B. Swain and J. Magill, who believed that combining treatment techniques could enhance the treatment process. Scientific evaluation of light wires and light forces in orthodontics and the clinical applications were built through the work of H. Barrer, R.P. Begg, H. Kesling and R. Rocke. Segmental arch mechanics as designed by C. Burstone and T. Mulligan with Mulligan mechanics also assisted in this evolution. Dynamic and interactive force systems were brought into the edgewise arena by individuals like C. Tweed, M. Stoner, R. Ricketts and R. Isaacson.

During this metamorphosis of orthodontic appliance systems there developed an approach that combined both the light wire philosophy of moving teeth and the accuracy of edgewise finishing. By virtue of its combination of techniques there was an additional system created that originated as the IV stage technique (Fig. I.1). This approach to the correction of malocclusion included the first three stages of the Begg technique, utilizing round wires and gingival slots with V-bends and light elastic force. It finished

with square wire pre-angulated and torqued, edge-wise mechanics. Light forces (1–3 oz) in conjunction with small round wires (0.014"–0.018") combined with V Intrusion bends allowed for rapid tooth movement and bite opening (Fig. I.2). The use of auxiliaries and springs to segmentally or individually correct tooth positions was included (Fig. I.3). This allowed for minimal adjacent or additional anchorage requirements and could be placed on one tooth without archwire removal or adjustment. The system also provided a considerable freedom of movement via one-point contacts of archwires in the 256 Begg or IV stage bracket's gingival slot. A pin or tie-wire was used to secure the archwire and provide the uni-point contact between the archwire and the bracket resulting in this large amount of



Fig. I.2 Typodont view indicating the extent of intrusion activation before engagement.



Fig. I.1 A representative stage three of treatment with the IV stage technique, depicting Begg mechanics.



Fig. I.3 A IV stage bracket technique, with Begg mechanics, illustrating the use of uprighting springs.

freedom and tipping. The freedom of movement is a current goal of the self-ligating systems.

Whereas the IV stage technique was popular to Begg operators, it still required an intrinsic knowledge of complex Begg biomechanics. Therefore the next natural transition was to incorporate the two-slot IV stage systems into one and do it simultaneously. This required a new bracket design; this was accomplished by Cannon and Thompson in the late 1970s and was called CAT (combination anchorage technique). The CAT technique evolved through the training and education of followers and contributors such as B. Thompson, N. Sakai, J. Fanno, J. Rossetti, H. Lerner, J. Cannon, J. Thompson and A. Zacs. It developed into a multiple slot/technique approach with consideration for anchorage via bracket and archwire slot position and the resultant changes in friction. The reference to free tipping movement vs high force, rigid resistance was made, and static and dynamic anchorage was developed. Additionally, light force systems were being designed to optimally utilize 'root surface' resistance or anchorage. This anchorage was created during tooth movement by differences in surface areas that required metabolic bone turnover. Simply put, it was the ability to pit different size and number of roots against each other in specific ways allowing for variability in tooth movement (Fig. I.4).

Increased interbracket distance was an advantage and could be altered as a factor of which slot the archwire was placed in (Fig. I.5). The same advantages were realized and put to use in other combination systems like Tip-Edge. Resistance anchorage was created between the effect of round or square wires sliding or binding in three-sided edgewise slots or tipping in uni-point slots. These uni-point slots (both gingival and incisal) became critical in the development of the next combination system called the VAST, utilizing the Spectrum 441 bracket.

VAST stands for variable anchorage straight-wire technique. It incorporated a single bracket providing

four slots into which one or two archwires could be secured. The slots included a 0.018" or 0.022" edgewise slot, a 0.020" gingival slot, a 0.020" incisal slot and a vertical auxiliary 0.020" slot. It was the 'light wire system' expanded out to the maximum in treatment possibilities thus far. Compared to the force systems used in the current self-ligating bracket therapies, all were included and the available variation in bracket utility was not as restricted. Each Spectrum 441 bracket could be secured a number of different ways (Fig. I.6), allowing for huge variation in activation force, resistance and anchorage designs. VAST therapies developed rapid bite opening and class II correction with light physiological forces, the same as are being reported with the present day self-ligating bracket systems.

The current Spectrum bracket of the VAST can be utilized as a light wire bracket in early treatment with V-bend and wing slot mechanics, similar to segmented arch and Mulligan mechanics. During space closure or the uprighting segment of therapy, 'tandem arch' mechanics transitioned into the final edgewise guidance and finishing phase (Fig. I.7). The consistency and low level of force is similar to those of self-ligating packages. Therefore the bite opening was maintained, while root parallelism and uprighting was initiated, without opening up interproximal spaces; optimal edgewise mechanics followed, with full size rectangular archwires in the pre-angulated, pre-adjusted straight-wire slots (Fig. I.8).

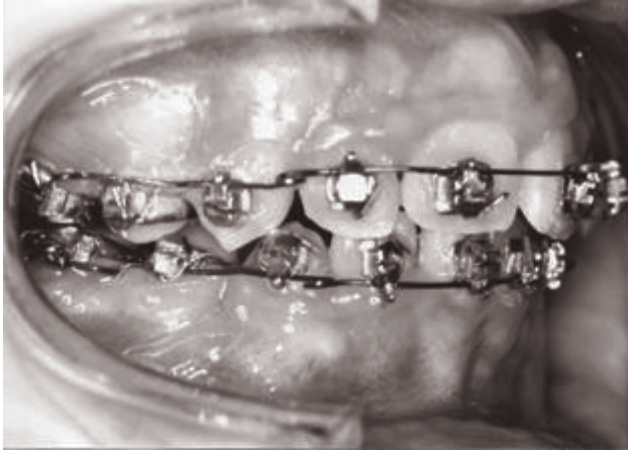
There are numerous recent systems that are being designed attempting to include the multitechnique therapy with the advantage and speed of self-ligation. Each bracket attempts to 'borrow' from all previously created systems and to improve the efficiency, size, esthetic nature, ligation style and resistance requirements. These will continue to evolve as operators continue to design new mechanical systems addressing specific anchorage and movement requirements, in order to create the most ideal facial, functional and occlusal results.



a



b



c



d



e



f



g

Fig. 1.4 (a–g) Buccal view of a case treated with four premolars extraction using the combination anchorage technique (CAT).

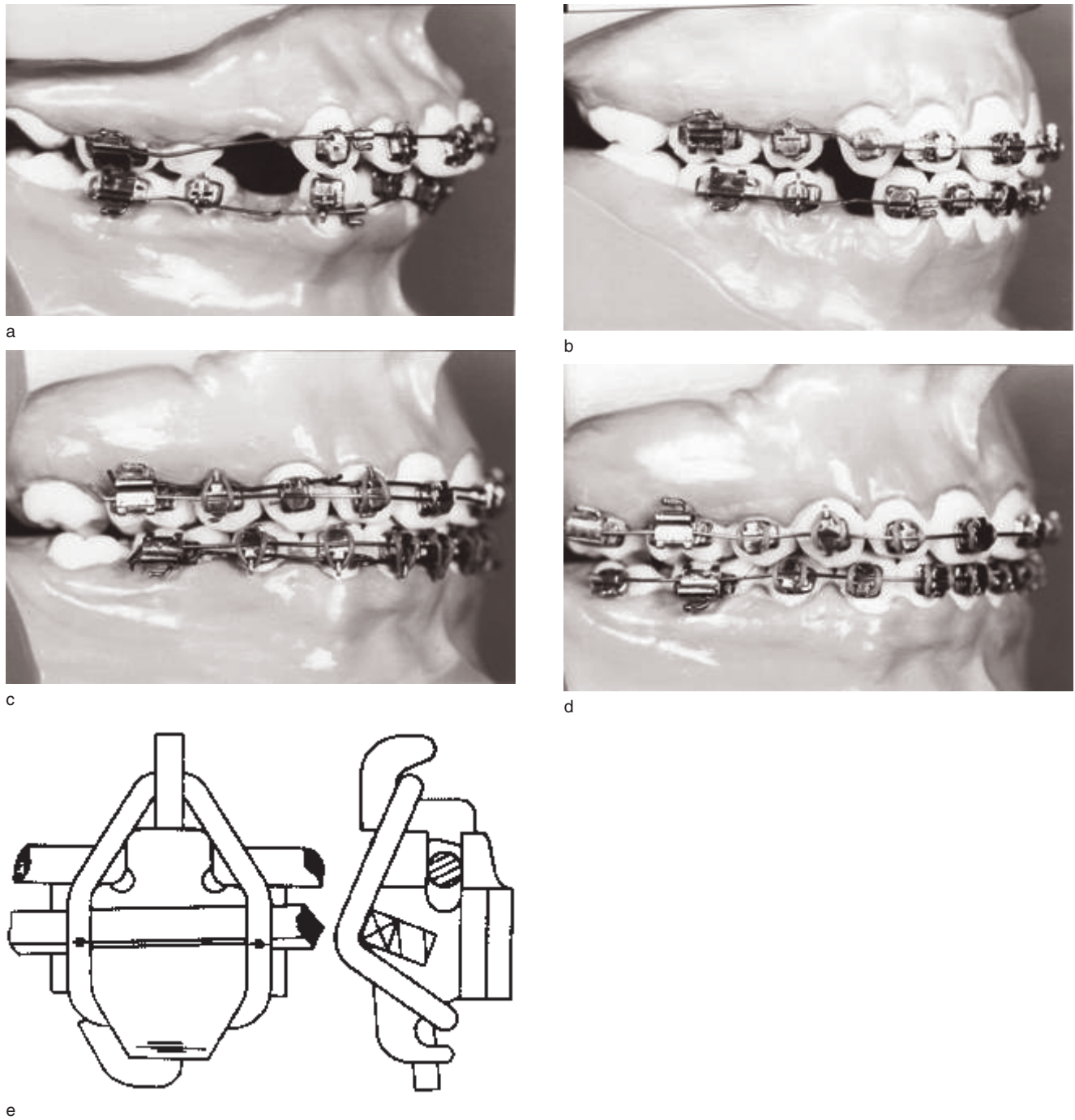
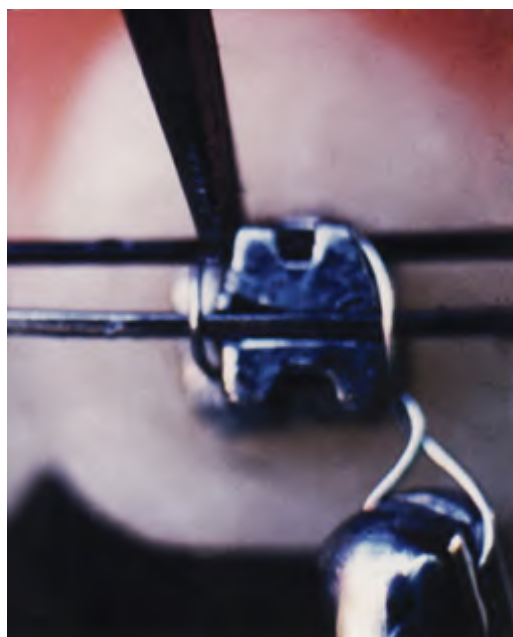


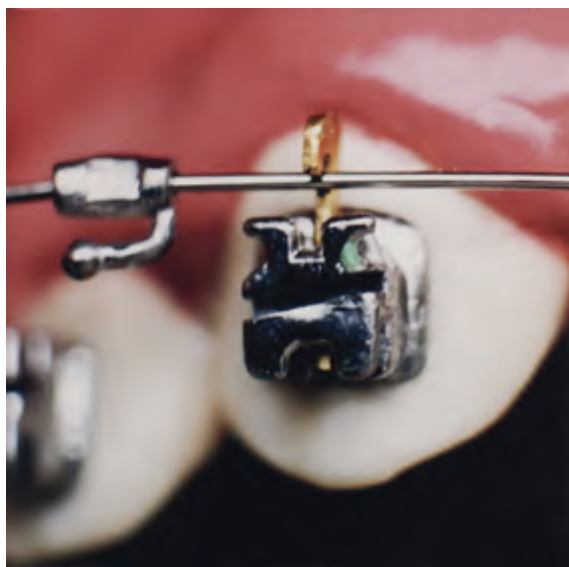
Fig. 1.5 Typodont view of various stages of extraction treatment with the CAT appliance. (a) Initial engagement; (b) phase II, space closure; (c) phase III, paralleling; (d) phase IV, finishing; (e) tandem dual archwires.



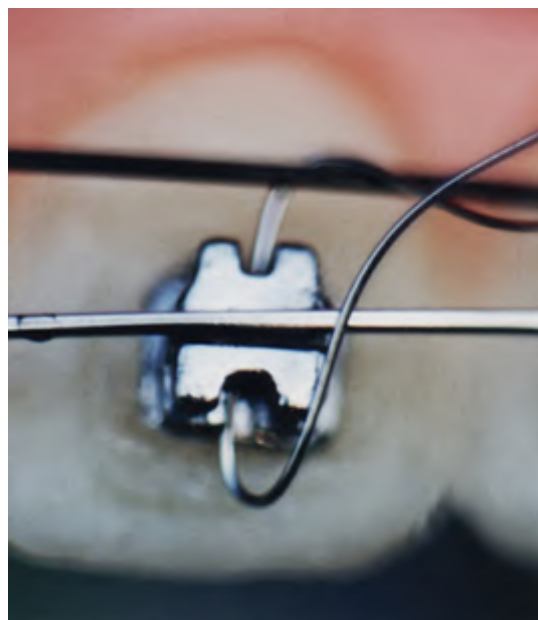
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Fig. 1.6 (a–d) Intraoral views of various methods to engage archwire into the bracket slots with the Spectrum 441 appliance.

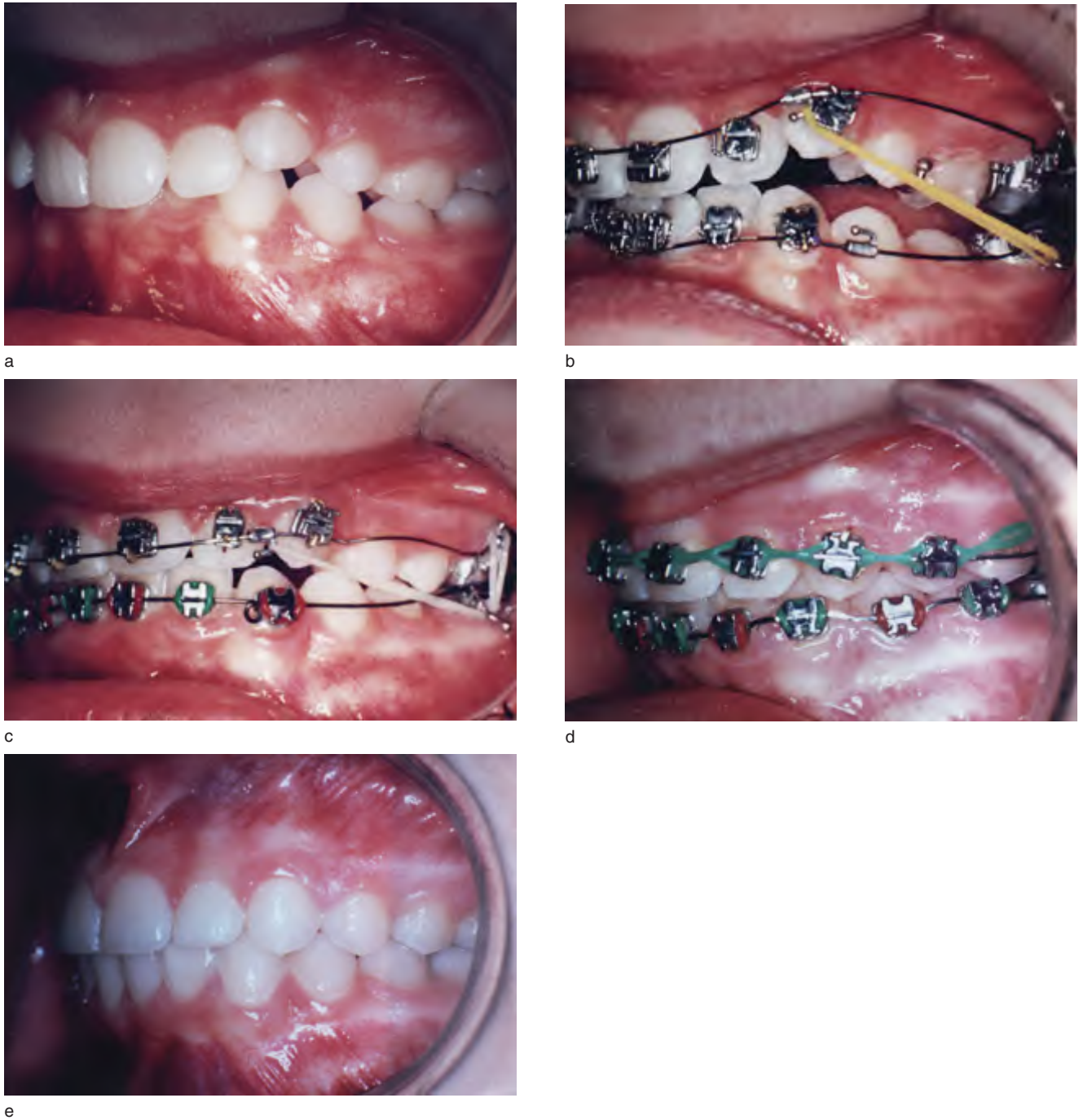


Fig. 1.7 A case illustrating the treatment mechanics sequence in non-extraction therapy using the variable anchorage straight-wire technique (VAST). (a) Pre-treatment; (b) V-bend bite opening in wing slot; (c) edgewise slot transition; (d) finishing–levelling; (e) post-treatment.



a



b



c



d



e

Fig. 1.8 Intraoral buccal views of a class II division 2 malocclusion treated with variable anchorage straight-wire technique (VAST) demonstrating the efficiency of bite opening, and its maintenance during mechanics. (a) Pre-treatment; (b) early wing slot; (c) tandem transition; (d) edgewise straightwire finishing; (e) post-treatment.

1

Historical Aspects and Evolution of Ligation and Appliances

Nigel W. T. Harradine

INTRODUCTION

The vast majority of fixed orthodontic appliances have stored tooth-moving forces in archwires which are deformed within their elastic limit. For this force to be transmitted to a tooth, wires need a form of connection to the bracket which is in turn fixed to the tooth. This connection has for many years been referred to as 'ligation' because the early forms of connection were most frequently a type of ligature and this remained the situation for several decades. All more recent forms of connection between bracket and archwire have retained the title of ligation. 'Elastomeric ligatures' and 'self-ligating brackets' are firmly established orthodontic terms. This chapter aims to outline the history and development of archwire ligation and to put self-ligation into this perspective.

EARLY LIGATURES

The earliest ligatures were often made from silk which had long been used in surgery for suturing. When stainless steel became available, this was universally adopted. Stainless steel ligatures have several inherent qualities. They are cheap, robust, essentially free from deformation and degradation and to an extent they can be applied tightly or loosely to the archwire. They also permit ligation of the archwire at a distance from the bracket. This distant ligation is particularly useful if the appliance tends to employ high forces from the archwires, because this high force prevents sensible full archwire engagement with significantly irregular teeth. Ironically, as will be discussed later, wire ligatures have contributed to such higher forces through the friction they

generate. In spite of these good qualities and their widespread use over many decades, wire ligatures have substantial drawbacks and the most immediately apparent of these is the length of time required to place and remove the ligatures. One typical study¹ found that an additional 11 minutes was required to remove and replace two archwires if wire ligatures were used rather than elastomeric ligatures. Additional potential hazards include those arising from puncture wounds from the ligature ends and trauma to the patients' mucosa if the ligature end becomes displaced.

ELASTOMERIC LIGATURES

Elastomeric ligatures became available in the late 1960s and rapidly became the most common means of ligation, almost entirely because of the greatly reduced time required to place and remove them when compared with steel wire ligatures. It was also easier to learn the skills required to place these ligatures, so new clinicians and staff greatly preferred elastomerics. Intermaxillary elastics had been employed since the late nineteenth century, pioneered by well-known orthodontists such as Calvin S. Case and H.A. Baker. Initially these elastic bands were made from natural rubber but production of elastomeric chains and ligatures followed the ability to produce synthetic elastics from polyester or polyether urethanes. The ease of use and speed of placement of elastomeric ligatures did, however, lead to other definite disadvantages being generally overlooked, although readily apparent. Elastomerics frequently fail to fully engage an archwire when full engagement is intended. Twin brackets with the ability to 'figure of 8' the elastomerics are a signifi-

cant help in this respect, but at the cost of greatly increased friction (*vide infra*). A recent paper by Khambay *et al.*² quantified the potential seating forces with wire and elastic ligatures and clearly showed the much higher archwire seating forces available with tight wire ligatures. A second and well-documented drawback with elastomerics is the substantial degradation of their mechanical properties in the oral environment. A comprehensive literature review of elastomeric chains³ gives a good account of the relevant data and a more recent article⁴ discusses the underlying reasons and clinical significance of this loss of mechanical properties. Typically elastomeric chains and ligatures suffer more than 50% degradation in force in the first 24 hours⁵ when tested under *in vitro* experimental environments. The higher temperature in the mouth, enzymatic activity and lipid absorption by polyurethanes are all cited as *in vivo* sources of force relaxation. This leads to the well-known potential for elastomeric ligatures to fail to achieve or to maintain full archwire engagement in the bracket. Fig. 1.1 shows the familiar loss of rotational control of canines during space closure whilst the molar teeth have retained excellent archwire control through their rigid molar tubes. Fig. 1.2 shows a generalized loss of rotational control due to these shortcomings. Twin brackets with the ability to 'figure of 8' the elastomerics are a significant help in this respect but certainly not a complete answer.

A further factor of potential clinical importance is the variability in mechanical properties of elastomerics. This is well described by Lam *et al.*⁶ who reported substantial variation in the range and tensile strength of elastomerics from different manufacturers and for different colours of elastomeric from the same manufacturer.

Lastly, there is a large body of literature to demonstrate the much higher friction between bracket and archwire *in vitro* with elastomeric ligation compared to wire ligatures. This had been proposed as a factor of clinical significance more than 30 years ago⁷. A recent and representative study which demonstrates this difference in friction well is by Hain *et al.*⁸ The potential importance of friction and its relation to forms of ligation will be discussed in more detail below.

The great popularity of elastomeric ligation in the last 40 years was achieved in spite of these substantial deficiencies in relation to wire ligatures. Speed



Fig. 1.1 Conventional elastomeric ligatures failing to maintain full bracket engagement on three of the six ligated teeth.



Fig. 1.2 Loss of rotational control by elastomeric ligatures on five teeth.

and ease of use was the over-riding asset of elastomerics and it is no surprise that the strongest motivation behind the early efforts to produce a satisfactory self-ligating bracket was a desire to have all the benefits of wire ligation but in addition to have a system which was quick and easy to use.

BEGG PINS

In the 1950s, Raymond Begg, a former pupil of Edward Angle, developed his light wire technique using Angle's ribbon arch brackets with round wire archwires⁹. A key feature of the technique was the use of brass pins as the method of ligation. These pins constituted the fourth (gingival) wall of the bracket slot and formed a rigid metal wall analogous

in some ways to that of a molar tube or a self-ligating bracket. The pins were designed with shoulders to keep from binding the archwire in the early alignment stages and as 'hook-pins' they held the archwire in a more precise vertical position when thicker wires and auxiliaries were added later in the treatment. This author used many such pins, being trained simultaneously in Begg and edgewise mechanics during his initial specialist training. Begg pins had none of the disadvantages of elastomeric rings and were probably more rapid to place and remove than wire ligatures. These pins cannot be assessed in complete isolation from the rest of the Begg technique, but, in relation to self-ligation, it is well worth noting the reputation that the Begg technique acquired for rapid early alignment and the effectiveness of lighter forces when there was no friction from tight engagement with elastomerics to be overcome. As a footnote in orthodontic history, it should be recalled that self-ligating Begg brackets were produced in the 1970s and were used by this author on a number of cases. They had an inbuilt pin which was rotated into position over the archwire with the intention being to further simplify and speed the process of ligation. This development was overtaken by the development of better overall bracket systems in the 1970s – most notably the straight-wire appliance. Interestingly, when the tip-edge appliance was developed to be a successor to the Begg technique, it abandoned the metal, low-friction form of ligation which Begg pins represented and reverted to elastomerics.

SELF-LIGATION

Self-ligating orthodontic brackets have a relatively long history, but their development can best be viewed against the background of an almost universal use of elastomeric ligatures in spite of the known advantages of wire ligatures – and in a different context, of brass Begg pins. Elastomeric ligation gives unreliable archwire control, high friction, and an added oral hygiene challenge, although no data is available to indicate that conventional ligation results in more microbial attachment to appliances compared to their self-ligating counterparts. Wire ligation is better in every respect, but is very slow, inconsistent in its force application and the wire ends can cause trauma to patient and operator. It is

easy to find examples of the deficiencies of conventional ligation, but clinicians have become accustomed to tolerating these shortcomings. Self-ligation offers the opportunity for very substantial improvements in relation to all of these drawbacks, but for many years remained the choice of a small minority of clinicians.

Self-ligating brackets by definition do not require an elastic or wire ligature, but have an inbuilt mechanism which can be opened and closed to secure the archwire. In the overwhelming majority of designs, this mechanism is a metal face to the bracket slot which is opened and closed with an instrument or finger tip. Brackets of this type have existed for a surprisingly long time in orthodontics – the Russell Lock edgewise attachment being described by Stolzenberg¹¹ in 1935. This was by modern standards a very primitive mechanism consisting of a labial grub-screw to retain the archwire. Many designs have been patented although only a minority has become commercially available. Table 1.1 is not

Table 1.1 Examples of self-ligating bracket designs.

Self-ligating bracket	Year
Russell Lock	1935
Ormco Edgelok	1972
Forestadent Mobil-Lock	1980
Forestadent Begg	1980
Strite Industries SPEED	1980
'A' Company Activa	1986
Adenta Time	1996
'A' Company Damon SL	1996
Ormco TwinLock	1998
Ormco/'A' Co. Damon2	2000
GAC In-Ovation	2000
Gestenco Oyster	2001
GAC In-Ovation R	2002
Adenta Evolution LT	2002
Forestadent lingual	2002
Ultradent OPAL	2004
Ormco Damon3	2004
3M Unitek Smartclip	2004
Ormco Damon 3 MX	2005
GAC In-Ovation L	2005
Ultradent OPAL metal	2006
Forestadent Quick	2006
Lancer Praxis Glide	2006
Class 1/Ortho Organisers Carrière LX	2006
GAC In-Ovation C	2006
Clarity SL	2007
American Orthodontics Vision LP	2007

exhaustive but includes a majority of the brackets produced commercially since that time. New designs continued to appear, notably the SPEED bracket (Strite Industries Ltd, 298 Shepherd Avenue, Cambridge, Ontario, N3C 1V1 Canada) in 1980. The Time bracket (Adenta GmbH, Gliching, Germany) becoming available in 1994, the Damon SL bracket ('A' Company, San Diego, California) in 1996 and the TwinLock bracket ('A' Company, San Diego, California) in 1998, were three representative designs from that decade. Since the turn of the century, the pace of development has greatly accelerated with the launch of at least 16 new brackets and rapidly increasing sales for such brackets. An overview of the status of self-ligation early in the current decade¹² summarizes the situation at that time. Recent years have seen a continuation of rapid changes in bracket technology, an expansion of the advocated advantages and a much greater research effort to gather the related evidence.

Proposed core advantages of self-ligating brackets

In the last two decades, a consensus has emerged on the potential core advantages of self-ligation. These can be summarized as: faster archwire removal and ligation, more certain full archwire engagement, less or no chairside assistance and low friction between bracket and archwire

Faster ligation

This should be discussed first because historically, it was the most powerful incentive to develop self-ligating brackets in the era of wire ligation. The relative slowness of wire ligation has already been noted¹. Several studies have also shown that self-ligation offers savings in chairside time compared to elastomeric ligation. One relatively early study¹³ found a 10 minute saving in time when comparing the removal and replacement of ligation on just the anterior 12 teeth in a pair of archwires.

Secure archwire engagement

It seems self-evident that a solid, reliable and robust form of ligation which cannot break or suffer decay in its ligating force is a desirable characteristic. Self-

ligating brackets have varied in their robustness and reliability but several current brackets have mechanisms which deliver this advantage and the consequent enhanced control of tooth position.

Low friction

Wire ligatures produce substantially lower friction forces than elastomerics¹. However, the forces generated by wire ligation still reach high and very variable levels² relative to those force levels which are thought to be optimal for tooth movement. There is now a large body of work detailing the very low levels of friction available with self-ligating brackets *in vitro*. Much of the earlier work was on brackets aligned in a passive configuration relative to the archwire. These all showed a dramatic reduction in friction with self-ligating brackets, especially those with passive slides. A representative paper¹⁴ is from 1998. Fig. 1.3 shows the frictional resistance with four brackets and increasing wire sizes. For the passive self-ligating bracket (Damon SL) no friction was detectable until the wire is 0.019"/0.025". The self-ligating bracket with the active clip (Adenta Time) has rather more friction but this is still very much less than the friction with 'A' Company standard Straight-Wire brackets and TP Tip-Edge brackets, both of which were ligated with elastomerics ligatures. A typical study¹⁵ found that the friction per bracket was 41–61 g (depending on the archwire) with conventional brackets and conventional ligation and 3.6–15 g with Damon brackets. However, it was readily apparent that, *in vivo*, the archwires are active in varying degrees and directions and that this will add substantially to the resistance to sliding. Many more recent experimental designs have therefore investigated the effect of archwire activation on resistance to sliding.

Three papers by Thorstenson and Kusy in this area are particularly recommended^{16–18}. In 2001, these authors examined the effects of varying active tip (angulation) on the resistance to sliding. They found that angulation beyond the angle at which the archwire first contacts the diagonally opposite corners of the bracket slot causes a similar rise in resistance to sliding of both self-ligated (Damon SL) and conventional brackets. However, at all degrees of tip, the Damon brackets produced significantly less resistance to sliding (Table 1.2). At a realistic angulation of 6° for a 0.018" × 0.025" stainless steel

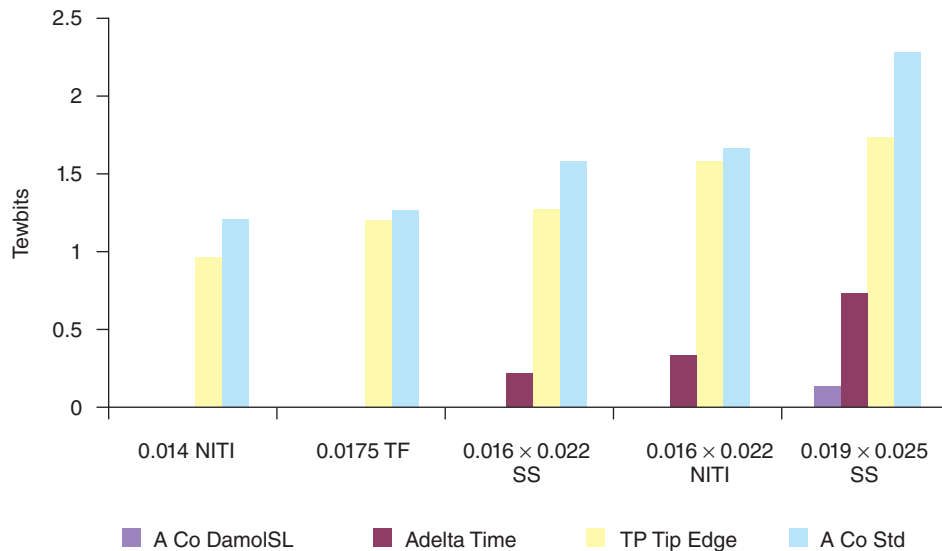


Fig. 1.3 Data from Thomas *et al.* (1998)¹⁴ showing the typically very low friction for self-ligating brackets when compared to conventional ligation.

Table 1.2 Resistance to sliding (RS) for different bracket angulations with a 0.018/0.025 archwire. Forces in cN. Data from Thorstenson and Kusy (2001)¹⁶.

Angulation (degrees)	Damon SL	Conventional bracket
0	0	34
3.5	0	55
6.0	80	140

wire, the difference of 60 g is very probably of clinical significance. The second paper¹⁷ compared different self-ligating brackets for resistance to sliding with active angulations. It quantifies a little more closely the lower resistance to sliding with passive self-ligation and points out that low resistance to tooth movement can also lead to unanticipated movement. The third paper¹⁸ examined the same factors with wires of different sizes and in the dry state. The increase in friction when larger wires deflect the clips in active self-ligating brackets is quantified and the scanning electron micrographs of the different brackets show very clearly the relationship between small and large wires and active clips and passive slides. Table 1.3 contains data from another study¹⁹ in which a known tipping (angulation) moment was applied to brackets able to tip up to 20° and the resistance to sliding was termed dynamic friction and measured for the four bracket types. The reduced friction for both types of self-ligating bracket can be seen and the difference between In-Ovation (active clip) and Damon2 (passive slide) was statistically and probably clinically significant. The study supports the view that

Table 1.3 Mean dynamic friction for different brackets with an applied tipping moment on a 0.019/0.025 stainless steel archwire. Forces in cN. Data from Mah *et al.* (2003)¹⁹.

Bracket	Transcend			
	Minitwin	600	In-Ovation	Damon2
RS in cN	379	455	238	99

self-ligation – and particularly passive self-ligation – produces substantially less resistance to tooth movement along an archwire even when the additional archwire activations found *in vivo* are present. Clinically, the low friction is very evident from the need with self-ligation to place a stop on all archwires to prevent the strong tendency for the archwire to slide through the brackets and traumatize the mucosa distally (Fig. 1.4).

Friction must be overcome for the majority of tooth movements to occur. Such movements include leveling, bucco-lingual alignment, rotation, correction of angulation, opening of space and any space closure with sliding mechanics. Frictional forces arising from the method of ligation are one source of the resistance to this relative movement between archwire and bracket. Correspondingly higher forces must therefore be applied to overcome this resistance and this has two related potential effects which inhibit tooth movement. Firstly, the net effective force is much harder to assess and is more likely to be undesirably higher than levels best suited to create the optimal histological response. Secondly, the binding forces are higher both between bracket and



a



b

Fig. 1.4 (a, b) An 0.018"/0.025" nickel–titanium wire displaced to the patient's left (Damon2 brackets). This is a frequent unwanted result of the low friction with self-ligating brackets if no stop is placed on the archwire.

wire and also at the contacts between irregular adjacent teeth. These binding forces also inhibit the required relative movement between bracket and wire. Only a few tooth movements such as space closure with closing loops placed in the space, expansion of a well-aligned arch, and torque (inclination) changes are not influenced by a low-friction method of ligation.

Assistance to good oral hygiene?

Bacterial accumulation has been proposed as a potential disadvantage of elastomeric ligatures and whilst there is some evidence which points in this direction, there is non-confirmatory or contradictory evidence which makes this as yet undetermined. It is a prevalent anecdotal view that elastomerics accumulate plaque more than do wire ligatures and there is some evidence to support this²⁰. There is also some evidence that wire ligatures reduce bleeding on probing of the gingival crevice when compared with elastomerics²¹. However, a scanning electron microscopy study²² found no difference in bacterial morphotypes when using elastomerics or steel ligatures. Several further studies are in progress, but as yet, there is no evidence to support the proposed microbiological advantages.

More comfortable treatment?

It has been proposed that the lower forces and less friction will result in less discomfort for the patient.

Two recent studies from the same centre have investigated this. In one study²³ Damon3 brackets were found to give the same discomfort as conventionally ligated Synthesis brackets. The other study²⁴ found no difference between SmartClip and conventionally ligated Victory brackets between patient visits, but a marked increase in discomfort when removing archwires through the Smartclip clips. Differences in design of specific self-ligating brackets can have important consequences. Miles *et al.*²⁵ did report lower discomfort initially but higher discomfort at a later stage with Damon2 brackets, but overall, there is currently little evidence that self-ligation is beneficial in this respect.

The core list of the advantages now has a fairly solid experimental basis, with better, more refined evidence appearing at frequent intervals. These advantages apply in principle to all self-ligating brackets although the different types of bracket may vary in their ability to deliver them consistently in practice. Advantages have also been proposed as resulting from the unique combination of low friction and good control which only self-ligating brackets (or molar tubes) can provide.

Secure archwire engagement and low friction as a combination

Other bracket types – most notably Begg brackets – have achieved low friction by virtue of an extremely

loose fit between a round archwire and a very narrow bracket, but this is at the cost of making full control of tooth position correspondingly more difficult. Some brackets with an edgewise slot have incorporated shoulders to distance the elastomeric from the archwire and thus reduce friction, but this type of design also produces reduced friction at the expense of reduced control. With tie-wing brackets, an improvement in control is usually at the cost of an increase in friction, especially with elastomeric ligatures. This point has been very nicely illustrated by Matasa²⁶. The combination of very low friction and very secure full archwire engagement in an edge-wise-type slot is currently only possible with self-ligating brackets (or with molar tubes). It has therefore been proposed¹² that this combination enables a tooth to slide easily along an archwire with lower and more predictable net forces and yet under complete control, with almost none of the undesirable rotation of the tooth resulting from a deformable mode of ligation such as an elastomeric. Sliding mechanics to move individual teeth is therefore a more attractive form of mechanics.

Possible anchorage consequences of the combination of low friction and secure full archwire engagement

Tooth movement has been shown in beagle dogs to be only partially related to the level of force applied²⁷. In clinical investigations²⁸, extremely good anchorage preservation has been shown where retraction

of individual canine teeth was pitted against an anchorage unit of the rest of the arch. This study using conventional brackets supports the clinical application of the differential force theory but use of this anchorage-preserving effect is inhibited by the tendency with conventional ligation for individual teeth to rotate when retracted along an archwire and then require realignment. Fig. 1.5 shows a clinical example of canine retraction with Damon SL brackets and undetectable anchorage loss. The hypothesis that self-ligation may increase available anchorage is therefore based on three possibilities: lower friction encourages the use of lighter forces which the differential force theory suggests would enhance anchorage preservation; individual teeth, e.g. canines, can be moved with no loss of rotational control; and faster treatment means less mesial drift and perhaps better co-operation? This proposal is handicapped by the current inconclusive evidence that treatment is faster with self-ligation.

All three of these proposals are plausible and in line with general anchorage theory, but currently lack robust and direct supporting evidence. These considerations apply equally to preservation of anterior anchorage in hypodontia cases where movement of individual teeth along an archwire is frequently required.

Alignment of severely irregular teeth

Crowded teeth have to push each other along the archwire to gain alignment. A combination of low

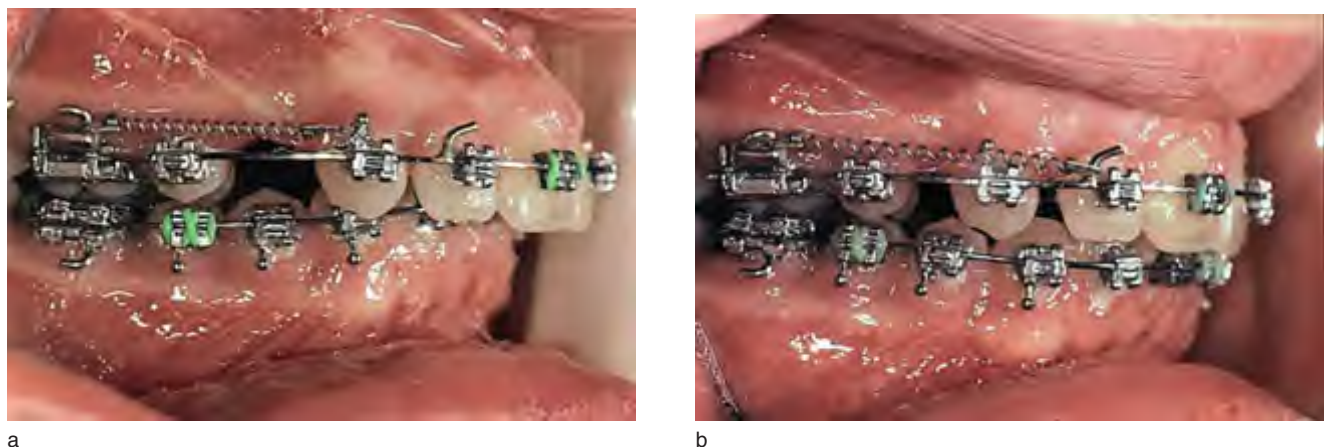


Fig. 1.5 (a, b) Retraction of an individual canine tooth with Damon SL self-ligating brackets on a 0.019"/0.025" stainless steel wire. No loss of anchorage or loss of rotational control of the canine is detectable.



a



b



c

Fig. 1.6 (a–c) Alignment (predominantly vertical) over two visits with Damon2 brackets and 0.012" wire. Very little adverse vertical movement of the central incisors is seen.

friction and secure full engagement should be particularly useful through enabling the wire to release from binding and slide through the adjacent brackets. This easy release of binding also serves to minimize adverse reciprocal tooth movements (Fig. 1.6). The relationship between friction and derotation has been described and quantified²⁹ and the potential adverse forces were shown to be very large. Fig. 1.7 shows the results of one visit derotating a tooth. Low friction should therefore facilitate rapid alignment whilst the secure bracket engagement permits full engagement and good control with severely displaced teeth. The evidence relating self-ligation to speed of alignment will be discussed later in this chapter.

Factors which have hindered the adoption of self-ligation

It is interesting and instructive to consider why, in spite of the potential advantages, self-ligation has

for so long and until so recently been a small part of orthodontics. In part this has been the result of imperfections in bracket performance. These imperfections have varied with different bracket designs and can be illustrated by examples from Table 1.1. The author of this chapter has used 15 of the types in this table.

In the opinion of this author, an ideal self-ligating bracket should deliver the core advantages already discussed and in addition should:

- Be very easy to open and close with low forces applied to the teeth during these procedures and with all archwire sizes and materials
- Never open inadvertently, allowing loss of tooth control
- Have a ligating mechanism that never jams or breaks or distorts or changes in its performance through the treatment period
- Have a positively held open clip/slide position, so that the clip or slide does not obstruct the view of

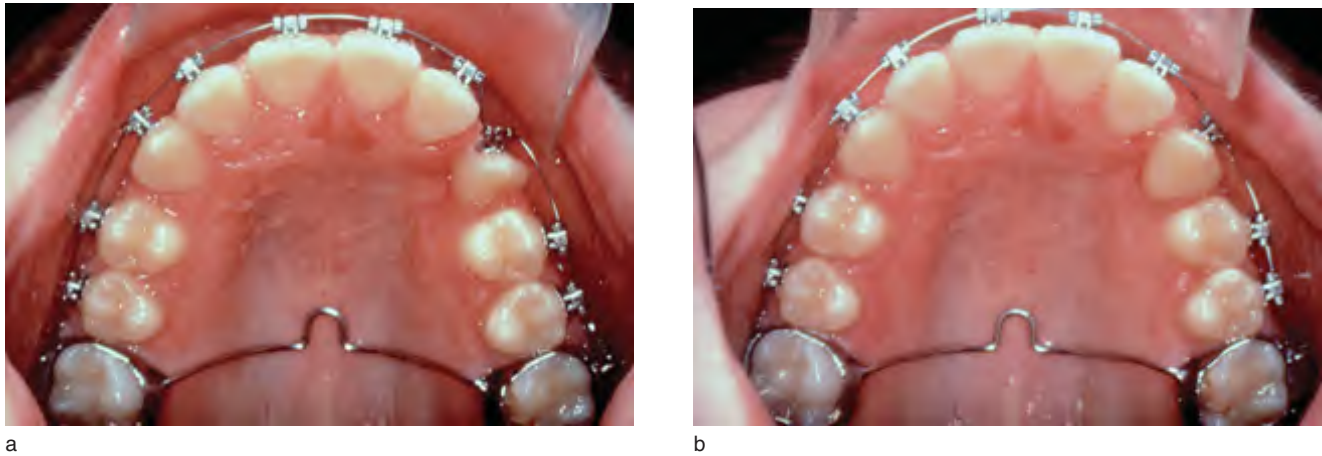


Fig. 1.7 (a, b) One visit of derotation of an upper canine on 0.012" wire and Activa self-ligating brackets. The inevitable initial bracket binding is able to release and pass the surplus archwire through the adjacent brackets as the tooth derotates.

the bracket slot or the actual placement of the archwire

- Be tolerant of a reasonable excess of composite material without obstructing the clip/slide mechanism
- Permit easy attachment and removal of all the usual auxiliary components of an appliance, such as elastomeric chain, undertie ligatures, laceback ligatures, without interfering with the self-ligating clip/slide
- Permit easy placement and removal of hooks/posts and possibly other auxiliaries on the brackets. With the security of self-ligation, the use of elastics directly to a bracket is much more frequently appropriate than with conventional ligation
- Have a suitably narrow mesio-distal dimension to take advantage of the secure archwire engagement and permit large interbracket spans.
- Have the performance expected of all orthodontic brackets in terms of bond strength and smoothness of contour

Many brackets have been less than satisfactory in several of these requirements and a representative selection can be used to illustrate the difficulties experienced over the years in producing the ideal bracket.

Edgelok brackets³⁰ (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) were the first self-ligating bracket to be produced in significant quantities. Disadvantages included inadequate rotational control, bulkiness and some inconvenience with



Fig. 1.8 Early example of a SPEED bracket. The bracket contained no retaining slot for the spring clip which led to spring distortion and loss of archwire control. A retaining slot was later incorporated.

opening and closing the slide and they were never widely adopted.

The well known **SPEED brackets**³¹ have remained in successful production since 1980. This testifies to the inherent soundness of many of the original design features. Early brackets (Fig. 1.8) were handicapped by clips which could too easily be displaced or distorted. These drawbacks have since been successfully addressed by improvements in the bracket body and in the clip itself, but combined with the inherent unfamiliarity for clinicians of a bracket with no tie wings, these aspects probably hindered the wider popularity of SPEED in previous years.



Fig. 1.9 Mobil-lock brackets showing the double cams required to establish sufficient labial slot face on the upper central incisor and the inadequate labial face on the lateral incisor. The 'screwdriver' was hard to use in the buccal segments.

Mobil-Lock brackets (Forestadent Bernhard Foerster GmbH, Westliche 151, 75173 Pforzheim, Germany) had a rotating cam which was turned with a 'screwdriver' thus covering part of the labial surface of the slot. The wire could be tightly or loosely engaged by the degree of rotation of the cam. These brackets were well engineered by the standards of the day, but a major limitation was the narrowness of the resulting labial face of the slot. This gave very poor rotational control to the extent that upper incisor brackets were given twin cams to increase the effective bracket width (Fig. 1.9). Another problem was the difficulty of access to open and close premolar brackets with the straight 'screwdriver'.

Activa brackets³² ('A' company, San Diego, California) had a rotating slide which therefore gave a concave inner radius to the labial surface of the slot. This increased the effective slot depth with small diameter wires, diminishing labio-lingual alignment with such wires. The slide was retained on the mesial and distal ends of the slot and this made for a wider than average bracket which reduced the interbracket span with the consequent disadvantages (Fig. 1.10). The slide was also prone to breakage. The absence of tie wings was an additional nuisance when placing the elastomeric chain and the unfamiliar shape of the early bonding base made bracket positioning more difficult. Finally, a combination of the design features substantially reduced bond strength. In



Fig. 1.10 Activa brackets showing the unwanted bracket width, the absence of tie-wings which enforced the elastomeric chain to be placed behind the archwire and the unusual bracket base which was intended to indicate the facial axis of the teeth but contributed to the poor bond strength. The premolar tooth has a later, more conventional bracket base.

spite of these substantial drawbacks, cases could be successfully treated which demonstrated the now familiar advantages of self-ligation, but the deficiencies of the design ensured that they were only adopted by a minority of enthusiasts.

The Time2 bracket (Adenta GmbH, Gliching, Germany) superficially resembles a SPEED bracket, but unlike the SPEED clip which has a vertical movement, the Time clip rotates into position around the gingival tie wing and rotates towards the occlusal rather than the gingival wall of the slot. Early versions suffered from displacement of the clips and important but subtle changes in clip design were needed to sufficiently reduce this tendency and ensure its continued availability and success. Early production examples of many self-ligating designs have needed significant modification. The negative effect of such initial problems with self-ligating brackets has sometimes hindered subsequent popularity even when the problems have been very largely overcome.

Damon SL brackets^{33,34} ('A' Company, San Diego, California) also became available in the mid 1990s and had a slide which wrapped round the labial face of the bracket. These brackets were a definite step forward, but suffered two significant problems – the slides sometimes opened inadvertently due to the play of the slide round the exterior of the bracket and they were prone to breakage due to work-hardening on the angles of the slide during manufacture



Fig. 1.11 Damon SL brackets showing the previous loss of a slide on the upper lateral incisor. The tie-wings have enabled elastomeric ligation to continue but the potential advantages of self-ligation have been lost on that tooth.

(Fig. 1.11). The study by Harradine (2001)³⁹, quantified these problems. In 25 consecutive cases in treatment for more than 1 year, 31 slides broke and 11 inadvertently opened between visits. This compared with 15 broken and lost elastomeric ligatures in 25 consecutively treated cases with conventional brackets, so the difference in ligation fragility was not enormous, but when a clinician has paid extra for a novel bracket design and the main design feature is not highly robust and is susceptible to inexpert handling from inexperienced operators, it has a definite negative effect on widespread adoption of that bracket. Nevertheless, these brackets generated a substantial increase in the appreciation of the potential of self-ligation.

Damon2 brackets (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) were introduced to address the imperfections of Damon SL. They retained the same vertical slide action and U-shaped spring to control opening and closing, but placed the slide within the shelter of the tie wings. Combined with the introduction of metal injection molding manufacture, which permits closer tolerances, these developments almost completely eliminated inadvertent slide opening or slide breakage and led to a further acceleration in the use of self-ligation. However, the brackets were not immediately and consistently easy to open and this aspect of functionality is important to the new user. Also, it was possible for the slide to be in a half-open position, hindering archwire removal or placement.



Fig. 1.12 Early Damon3 brackets. The mechanical linkage between the resin and metal components was subsequently strengthened to prevent this separation.



Fig. 1.13 Loss of resin tie-wings from early Damon3 brackets. An additional metal insert corrected this problem which was shown by finite element analysis to arise from repeated indirect occlusal stress.

Damon3 and Damon3 MX brackets (Ormco Corporation, 1717 W. Collins Ave., Orange, CA 92867) have a different location and action of the retaining spring and this has produced a very easy and secure mechanism for opening and closing. In addition, Damon3 brackets are semi-esthetic. However, early Damon3 production brackets suffered three very significant problems: a high rate of bond failure, separation of the metal from the reinforced resin components (Fig. 1.12), and fractured resin tie-wings (Fig. 1.13). These three problems all received fairly rapid and effective investigation and correc-

tion, but illustrate that it continues to be a significant challenge for manufacturers to extrapolate from the experience with prototype brackets in the hands of skilled enthusiasts to subsequent full-scale production and the use by relative novices. The more recently launched all-metal Damon D3 MX bracket has clearly benefited from manufacturing and clinical experience with previous Damon brackets. As with other brackets, such as SPEED and In-Ovation (GAC International Inc., 355 Knickerbocker Avenue, Bohemia, NY 11716), it also features a slot for drop-in hooks, mentioned above in the list of ideal requirements.

In-Ovation R were originally called In-Ovation brackets and are very similar to the SPEED bracket in conception and design, but of a twin configuration with tie wings. Both of these additional features probably contributed to a greater acceptability of these brackets to the new user than the long-established SPEED brackets. In 2002, smaller brackets for the anterior teeth became technically possible and available – In-Ovation R (R for reduced, referring to the reduced bracket width) and this narrower

width was desirable in terms of greater interbracket span. The bracket subsequently became known as System R before reverting to the name In-Ovation R. They are a successful design (Fig. 1.14), but some relatively minor disadvantages in relation to the list of ideal requirements can be experienced (Fig. 1.15). Some brackets with this type of clip which moves vertically behind the slot are difficult to open and this is more common in the lower arch where the gingival end of the spring clip is difficult to visualize. Excess composite at the gingival aspect of brackets in the lower arch can be difficult to see and may also hinder opening. Similarly, lacebacks, under-ties and elastomerics placed behind the archwire are competing for space with the bracket clip. Interestingly, both SPEED and System R and also the similar and the more recent Quick brackets (Forestadent Bernhard Foerster GmbH, Westliche 151, 75173 Pforzheim, Germany) have aimed to address some aspects of this potential difficulty by providing a labial hole or notch in the clip in which a probe or similar instrument can be inserted to open the clip. The need to acquire the expertise of opening an unfamiliar



a



b



c

Fig. 1.14 (a–c) In-Ovation brackets facilitating the correction of a severely irregular malocclusion.



Fig. 1.15 In-Ovation R brackets. The small flexible clip is failing to maintain engagement of the archwire.

bracket can dishearten the new user of self-ligating brackets and these more recent refinements of the method of opening are a definite advance in this respect. These refinements are also typical of the incremental improvement of self-ligating brackets which can take place without being appreciated by clinicians who have experienced difficulties with earlier production examples.

SmartClip (3M Unitek 3M Center, St Paul, MN 55144–1000) retains the wire by two C-shaped spring clips either side of the bracket slot. The pressure required to insert or remove an archwire is therefore not applied directly to a clip or slide, but to the archwire which in turn applies the force to deflect the clips and thus permit archwire insertion or removal. This mechanism therefore has to cope with providing easy insertion and removal through the jaws of the clips but must also prevent inadvertent loss of ligation for both small, flexible archwires and large, stiff archwires. This is a difficult combination of requirements to balance satisfactorily (Fig. 1.16). Other spring clips such as on **SPEED** and **System R** brackets with their vertical action, have a rigid bracket component to assist the spring in resisting a loss of ligation and are opened vertically and independently of archwire placement or removal. It became apparent with wider clinical use that the force required for insertion and removal of thick stainless steel wires from SmartClip brackets was uncomfortably high. A recent modification has addressed this difficulty by lowering the effective stiffness of the spring clips.



Fig. 1.16 Early SmartClip brackets. The 0.018" nickel-titanium archwire was too uncomfortable for the patient to be engaged in these premolar teeth. The more recently developed spring clip addresses this by being less stiff. The easier archwire insertion has to be balanced with the requirement to keep all appropriate archwires engaged in the slot.

These examples all illustrate the difficulties which have been experienced by manufacturers aiming to meet the requirements of an ideal ligation system. The resulting imperfections in bracket design have undoubtedly slowed the adoption of self-ligation systems by clinicians in previous years. Current self-ligation designs have benefited greatly from previous clinical experience and from advances in the available production techniques such as metal-injection molding, laser forming and CAD/CAM technology.

Aside from the undoubted imperfections of many self-ligating designs, a further factor has possibly hindered the development and adoption of self-ligation. There has been an inherent conservatism amongst orthodontists who have tended to persist with the equipment and ideas given to them during their initial training. There has perhaps been an insufficient appreciation of what low friction, secure archwire engagement and light forces might achieve.

Esthetic self-ligating brackets

There have been three approaches to production of a more esthetic self-ligating bracket. Firstly, there are lingual self-ligating brackets. There are at least three lingual self-ligating brackets currently available. Forestadent (Bernhard Foerster GmbH,

Westliche 151, 75173 Pforzheim, Germany) have their lingual system, sometimes referred to as the Philippe bracket³⁵. The ligation mechanism involves deforming two retaining wings – with a Weingart plier to close and a spatula to open. This mechanism requires considerable care not to damage the enamel if an instrument slips and also the wings can be hard to open which can cause detachment of the bracket. Adenta (Adenta GmbH, Gliching, Germany) produce the Evolution bracket which is essentially a lingual version of the Time bracket produced by the same company, whilst the same applies to In-Ovation L from GAC. Ligation is inherently more difficult with lingual appliances, and an easy form of self-ligation clip or slide which can deliver the advantages of security and low friction are equally or even more valuable in that situation where the interbracket spans are inherently smaller. Combining a successful self-ligation mechanism with the particular lingual demands of low profile, easy archwire insertion, inbuilt bite ramps on some teeth and narrow bracket width is a demanding task. Further development is needed on this side of the teeth.

On the labial surface, Oyster (Gestenco Inc., PO Box 240, Gothenburg, Sweden) and OPAL (Ultradent Inc., 505W, 1200S, South Jordan, UT 84095) and Damon3 (partially) are resin brackets whilst Clarity SL (3M Unitek) and In-Ovation C (GAC) have been produced as ceramic brackets with metal clips. The potential limitations of resin polymers as a category of material for orthodontic brackets are well established. Oyster brackets were originally

found to be insufficiently robust. Recently they have incorporated a metal hinge with the intention of improving this. OPAL brackets were introduced later and have an ingenious design to address the challenge of the same material being very flexible in one part of the bracket to create a hinge, whilst providing as rigid a bracket slot and as reliable a clip as possible. This is not completely successful, but remains an imaginative use of polymer material. Good results can certainly be achieved, but as with all resin brackets, robustness and longevity are a challenge. Brackets with a semi-transparent labial clip also have to contend with the esthetic problem of food and debris collecting behind the clip where they are relatively inaccessible to oral hygiene measures (Fig. 1.17).

Ceramic brackets are long-established in orthodontics with their known strengths and drawbacks. Clarity SL and IN-Ovation C are likely to combine these properties with those of the corresponding metal self-ligating brackets already discussed. In-Ovation C has a rhodium-coated clip. It is possible that the optimal combination of self-ligation and esthetics will come from a breakthrough in the technology for coating metal brackets.

Active clip or passive slide

This is an issue which has attracted heated debate^{26,36} and continues to be stressed by many producers and advocates of particular brackets as a major feature



a



b

Fig. 1.17 (a) OPAL brackets on the day of placement in the upper arch. (b) The same patient at the next visit when the lower brackets were placed. The esthetic challenge posed by debris behind the semi-transparent labial clips is apparent.

of importance. Amongst the brackets in Table 1.1 which are currently available, SPEED, In-Ovation R and Quick brackets have a sliding spring clip, which encroaches on the slot from the labial aspect, potentially placing an active force on the archwire. Time2 brackets have a very similar clip, but for closure it rotates round a tie-wing rather than slides into place. These four brackets are all correctly described as having potentially active clips. In contrast, Damon brackets have a slide which opens and closes vertically and creates a passive labial surface to the slot with no intention or ability to encroach upon the slot and store force by deflection of a metal clip. SmartClip, Praxis Glide (Lancer, 253 Pawnee St, San Marcos, California 92069), Carrière LX brackets (Ortho Organisers, 1822 Aston Avenue, Carlsbad, California 92008–7306) and Vision LP (Appendix American Orthodontics, 1714 Cambridge Avenue, Sheboygan, Wisconsin 53081) are also passive systems.

The intended benefit of storing some of the force in the clip as well as in the wire is that in general terms a given wire will have its range of labiolingual action extended and produce more alignment than would a passive slide with the same dimension wire. With thin aligning wires smaller than 0.018" diameter, the potentially active spring clip will be passive and its activity irrelevant unless the tooth (or part of the tooth if it is rotated) is sufficiently lingually placed in relation to a neighboring tooth that the wire touches the inner surface of the clip. In that situation, a higher force will be applied to the lingually placed tooth with an active clip than with a passive slide. An active clip effectively reduces the slot depth from 0.027" (the depth for example of a Damon slot) to approximately 0.018". This shallower slot will potentially place more force for a given archwire which may have adverse consequences, but will provide a longer labio-lingual range of action with small diameter wires. With larger diameter wires, an active clip will place a continuous lingually directed force on the wire even when the wire has gone passive. The difference in labio-lingual range of action will be very small with such intermediate wires, but is one reason why 0.016" × 0.025" or 0.014" × 0.025" nickel titanium wires are recommended as the intermediate aligning wire for the passive Damon system. The paper by Thorstenson and Kusy¹⁸ contains scanning electron micrographs which show very clearly this relation-

ship between small and large wires and active clips and passive slides. It has been suggested that continued lingually directed force on the wire from an active clip will cause additional torque from an undersized wire, but the diagonally directed lingual force may not contribute to any effective third-order interaction between the wire corners and the upper and lower walls of the bracket slot, which is the origin of torquing force. Most types of active self-ligating brackets have therefore more recently addressed this question on upper incisors by extending a section of the upper and lower walls of the slot to act as 'torquing rails'. It is also suggested that a continual lingually directed force may assist with the accuracy of finishing a case, but this has not been demonstrated in the literature or indeed experienced by this author.

Overall advantages or disadvantages of an active clip

It is probable that with an active clip, initial alignment is more complete for a wire of given size to an extent which is potentially clinically useful. It is possible that the difference in effective force levels during alignment is sufficient to significantly change the archform which results from the alignment phase. With modern low modulus wires it is possible to subsequently insert thicker wires into a bracket with a passive slide and arrive at the working archwire size after the same number of visits as with an active clip – i.e. to store all the force in the wire rather than dividing it between wire and clip. The relative stiffness of archwires and the spring clip has not previously been well documented, but a recent study³⁷ demonstrated both a significant range of spring stiffness for In-Ovation R and SPEED brackets and also – for one bracket type (In-Ovation R) – an average halving of the spring clip stiffness during treatment. This variation and decay in spring force might have substantial biomechanical consequences. Finally, there are the questions of robustness, security of ligation and ease of use. Is a clip which is designed to flex, more prone to breakage or permanent deformation or to inadvertent opening or closing? This question has not been formally investigated. Studies involving the use of different self-ligating brackets in the same patient, or randomly assigned to different patients, are needed to test such hypotheses.

Further advantages claimed for self-ligation

More efficient treatment

Because self-ligation reduces the resistance to tooth movement and provides good security of wire engagement, it is natural to suggest that treatment might be more rapid. Several investigations have examined the hypothesis that self-ligation provides greater treatment efficiency in terms of length of treatment and number of visits, in addition to the reduction in chairside time which has been discussed earlier^{13,38}. More rapid treatment with fewer visits would clearly be an advantage from the patients' viewpoint and would also be more cost effective. Currently available self-ligating brackets are more expensive than most good quality tie-wing brackets. A modest balancing factor is the cost of elastic ligatures which are, of course, not required. However, this significant extra cost must be measured against any savings in time, which is an expensive commodity. The wider question is whether self-ligation enables shorter treatment overall.

A study of treatment efficiency by Harradine³⁹ found the following: a modest average time saving from a reduction in archwire placement/removal of 24 seconds per arch; a mean reduction of 4 months in active treatment time from 23.5 to 19.4 months; a mean reduction of four visits during active treatment from 16 to 12; and the same average reduction in peer assessment rating (PAR) scores for matched cases. These cases were treated in the 1990s with no change in extraction philosophy or treatment goals from concurrent treatment with conventional brackets.

A study by Eberting *et al.*⁴⁰ of intrapractitioner differences in three practices found an average reduction in treatment time of 7 months (from 30 to 25) and seven visits (from 28 to 21) for Damon SL cases compared to conventional ligation. In two of the three centres, the American Board of Orthodontics (ABO) irregularity scores were more improved with the Damon SL brackets to a statistically significant extent. These two studies support a view of clinically significant improvements in treatment efficiency with passive self-ligating brackets. The more recent bracket types would be expected to show still better treatment efficiency because they are less prone to breakage or loss of the clips and slides, are easier to open and close, are frequently of more effective slot

dimensions and are used with greater understanding of the optimal archwire selection and appointment intervals.

However, not all subsequent studies have found improvements in treatment efficiency. Five random controlled studies which between them compare Damon and Smartclip brackets with conventionally ligated brackets have examined the alignment phase of treatment^{25,41–44}. All five failed to find a significant overall increase in the speed of alignment, although Pandis *et al.*⁴² found that mild crowding was eliminated more rapidly with Damon2 than with conventional brackets in the hands of the same operator. Another study by Miles⁴⁵ found no improvement in the rate of en masse space closure with self-ligating brackets, although at that stage of the treatment, there was no relative movement between the archwire and the self-ligating brackets which were all mesial to the remaining spaces. It seems very probable that self-ligation does not confer a blanket advantage in treatment efficiency and that factors such as treatment interval, archwire sequence, extraction pattern and case mix are significant. Further studies are in progress with a variety of bracket types and this is a rapidly moving field of enquiry. Studies which have followed cases through to completion have yet to appear in print.

Qualitative differences in tooth movement with self-ligation

It would be incomplete when looking at the current situation with self-ligation not to mention some of the hypotheses about qualitative differences which have been put forward and which are currently being investigated. Essentially, these hypotheses reflect a proposal that self-ligation – and particularly passive self-ligation – enables tooth-moving forces to be sufficiently light that forces from the soft tissues can compete and interact with them. It is suggested that these lower forces can, for example, result in: wider arches which may be more esthetic; wider arches which have better periodontal health; wider arches which may be more stable; less incisor proclination for a given amount of crowding; less need for extractions; easier class 2 correction through a 'lip-bumper' effect.

These ideas are based on individual case reports and have generated much debate and subsequent studies. However, none of them has yet been directly

investigated to a stage where studies have been published.

Self-ligating brackets have a long history of sporadic development which has culminated in a recent explosive proliferation of bracket types. After many years of existence as a category of orthodontic bracket, they have finally come of age in terms of design, understanding and popularity. The motive for developing these brackets has progressively changed from a predominant desire for faster ligation to a search for a practical means of combining complete security of ligation with much lower friction. They are now sufficiently robust and user-friendly to reliably deliver most of their potential advantages. Whilst the core advantages of self-ligation are now well established, the proposals that self-ligation provides more rapid or qualitatively different treatment results are exciting and important, but are yet to be supported by formal investigations. We still have much to learn about the best use of self-ligation, but these brackets are clearly set to play a major role in orthodontic treatment for the foreseeable future.

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THE MATERIALS SCIENCE AND BIOMECHANICS OF SELF-LIGATION

2

The Significance of Bracket Material Properties in Orthodontic Mechanics

Theodore Eliades, Spiros Zinelis and William A. Brantley

INTRODUCTION

The evolution of the orthodontic appliance utilized to transmit loads from the wire to the tooth has shown remarkable fluctuations with periods of burst and quiescence succeeding each other. Throughout the course of orthodontics, the interest has shifted from the wire configurations seen in the early years of specialty, to the functional (wings, slot) and non-functional (base-wing joint) parts of the appliances, because of the introduction of low modulus wires, capable of applying forces of reduced magnitude for longer periods of time. The ‘functional’ parts may essentially affect the engagement of the archwire to the slot, the application of force to the tooth and bond survival throughout the full term of therapy. The non-functional mesh and base-wing joint, on the other hand, may not be actively utilized in treatment. However, their importance in bracket-retaining capacity and structural integrity is paramount.

Bracket material properties of conventional and self-ligating brackets alike are instrumental in modulating the performance of the appliances in the oral cavity. Whereas self-ligating brackets possess a moving part (the fourth wall of the rectangular slot), the three remaining walls (gingival, cervical and axial) are essentially the same. Therefore, the materials perspective is a key variable in projecting the response of the bracket to the engagement of an activated archwire. The effect of various material properties on clinically related variables is listed in Table 2.1.

The traditional approach in dealing with this subject in most textbooks involves the analysis of various mechanical properties derived from labora-

tory tests simulating friction in sliding mechanics. A thorough critique of this approach, which demonstrates the profound scientific incoherence of this type of experiment and lack of clinical relevance is provided in the chapter by Eliades *et al.* in the textbook *Orthodontic Materials*¹, where the typical friction testing setup is analysed and its inappropriateness is substantiated. However, the evidence available on the impact of various bracket components’ properties on clinical orthodontics is scarce and the existing limited sources are scattered in many articles.

The main objective of this chapter is to describe the role of each bracket component, i.e. base, mesh, wings and slot, and discuss aspects of manufacturing process and material properties as they relate to the clinical performance of the appliances, in a manner which could perhaps be described as ‘applied clinical metallurgy’. It follows that this chapter will not consider non-metallic brackets, such as plastic, composite and ceramic appliances. Fundamentals of these brackets have been extensively discussed in previously published texts and no breakthrough advances in raw materials or design and manufacturing have been noted in the past decade.

BRACKET BASE

The base of the bracket is either an integral part of the appliance in metal injection molded (MIM) appliances, or a separate component, which is joined to the wings with laser or soldering alloys. The clinically important properties of the base are focused on two parts: the *mesh*, and the *stiffness* (modulus of elasticity) of the base.

Table 2.1 Desirable properties of bracket components and their importance in mechanics.

Bracket component	Property	Effect on mechanotherapy/performance
Base	Low modulus of elasticity (E)	Ease in debonding (peel-off effect) because of plastic deformation of base
	Properly designed mesh	Sufficient interlocking of adhesive bond strength and expected reduced failure rate <i>in vivo</i>
Wings	High E	Resistance to deformation during engagement of archwires (especially torque)
Base–wing joint	Sufficient strength, low corrosion	Brazing alloys may show ionic release; metal injection molded appliances show high porosity and because they are made of one alloy are either too stiff for debonding or too compliant to resist plastic deformation during engagement; laser welding may seal parts superficially, however is currently superior to the other methods
Slot	High hardness and modulus	Structural integrity against the applied loads macroscopically (E), and microscopically (hardness)
	Low roughness	Full seating of wire into the slot, shielding against high forces arising because of decreased contact points between wire and slot
	Consistency and accuracy in size and prescription and proper shape	Full engagement of wire into the slot without excessive play and with delivery of bucco-lingual and mesial-distal inclinations as reported in prescription
Mesh	Grade of mesh	Micromechanical retention (interlocking of adhesive)
Overall	Low thickness	Better esthetics, minimum discomfort

Mesh

Mesh design is critical for the retention of the bracket to the adhesive layer through the impregnation of adhesive into the grooves incorporated into the mesh. Research has long indicated the optimum mesh size, which yields the highest bond strength². Excessively low and high density may be equally undesirable because of the inefficient interlocking and inadequate adhesive penetration, respectively. The difference found between the brackets tested with respect to base mesh may result from the different manufacturing processes employed for the production of the two appliances: the majority of brackets employ a standard system with a simple foil mesh pad to provide mechanical retention by the enormously increased active surface of the base. A wide variety of mesh formations has been employed to increase the effective surface area (Fig 2.1). Early studies, including research by Gwinnett in the 1970s³, determined the optimum mesh size for increased bond strength. Extensive analyses of the rheological properties of the adhesive pastes have been performed, and it has been found that viscosity is principally

controlled by the filler content volume of composite adhesives. The mesh pad is usually soldered in place with the use of electrical soldering.

Alternative modes of mesh or ‘pseudomesh’ designs include the plasma-sprayed bases, which have shown acceptable bond strength results for metallic brackets, and laser etching of the base to mimic the mesh design by forming grooves on the bracket base. Laser etching causes melting and evaporation of the metal, forming hole-shaped retentive features on the base. This treatment leads to higher bond strength: the literature indicates that stainless steel brackets with laser-structured retention demonstrated almost two times higher bond strength with enamel compared to simple foil mesh brackets⁴.

Stiffness

The stiffness of the base on the other hand, may modulate the response of the bracket to debonding handling (Fig. 2.2). A desirable peel-off effect necessitates the expenditure of the energy given to the appliance during debonding in the form of plastic

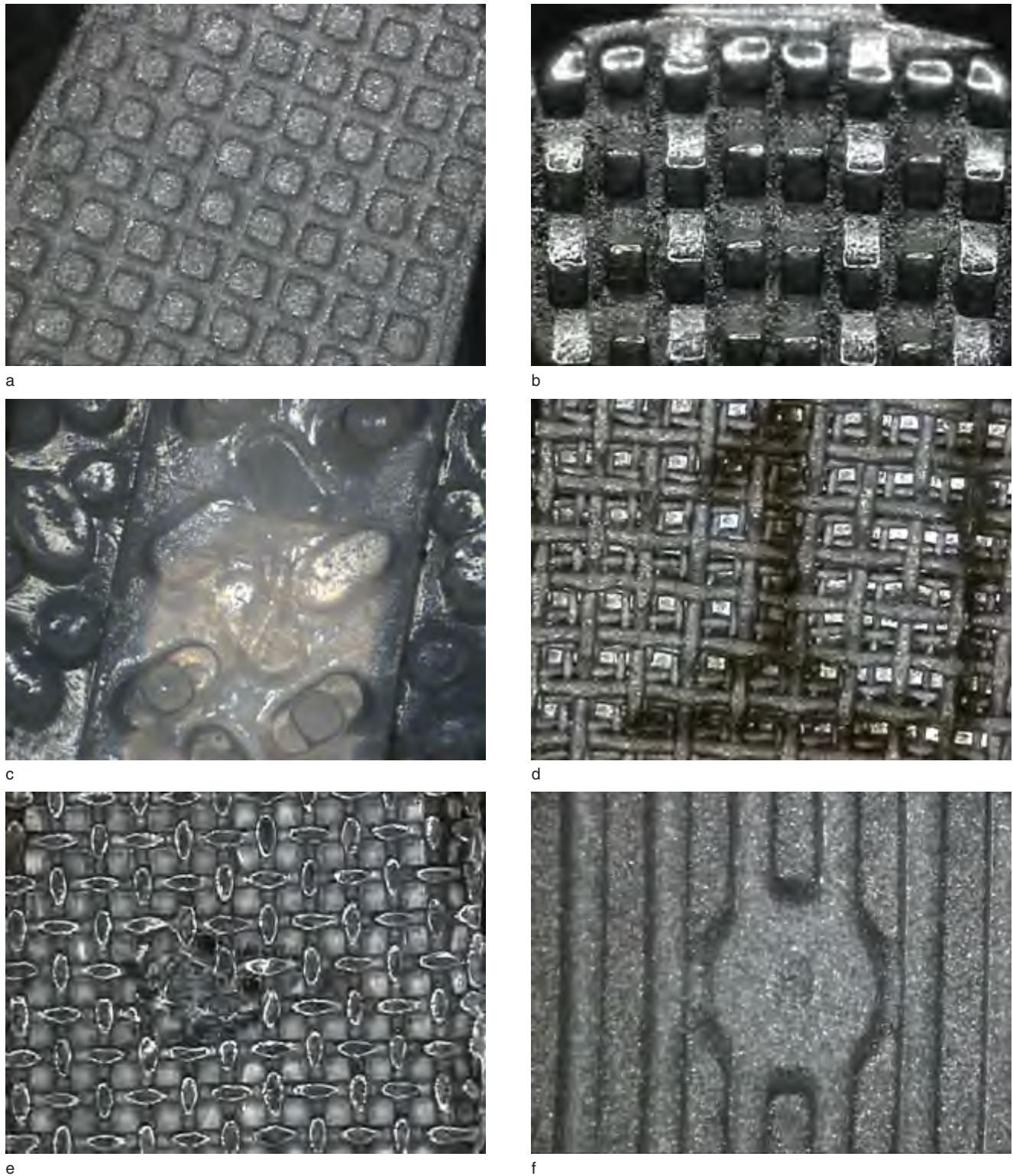


Fig. 2.1 (a–h) Reflected light microscopy images of various base mesh designs utilized in self-ligating brackets to provide interlocking with the adhesive.



g

Fig. 2.1 Continued.



h



Fig. 2.2 Reflected light microscopy image of etched base and wing of a bracket. Note the difference in size of the indentation arising from the variation in hardness of the appliance (larger pyramid implies softer alloy) (bright field 500 $\times$).



Fig. 2.3 A worn plastic wing of a metallic-plastic self-ligating bracket.

deformation. In this manner, the base is deformed, and the adhesive layer is fractured, with mostly cohesive failures showing in the enamel and bracket base. Plastic deformation usually occurs when soft alloys are used for the manufacturing of the bracket base, so that the sensitive and occasionally mobile teeth, especially mandibular incisors, are shielded from the loads applied with the debonding pliers.

WINGS

The wings of the bracket along with the slot comprise the most critical functional components of the

appliance in the sense that these parts are subjected to the loads applied during mechanotherapy. The clinical interest of this component relates to the resistance to fracture, which makes the bracket practically unusable because of the lack of ligating features. Wing fracture is almost absent in metallic appliances because of the ductility of the alloys used in bracket manufacturing; in essence the wing is plastically deformed and no fractures occur (Fig. 2.3). On the contrary, wing fracture or wing loss in ceramic and plastic brackets respectively, may be attributed to the brittle nature of the former and the fact that plastics are prone to degradation in severe environments, mainly attributed to temperature- and deformation-induced softening⁵.

The inner surface of the wing and its proximity with the slot wall necessitates the use of high modulus alloys to avoid plastic deformation, as this would allow dissipation of the load applied to the bracket as permanent deformation of the appliance, adversely affecting the application of force to the tooth.

BASE-WING JOINT

As a standard manufacturing process, the industry uses brazing alloys to join the base and wing components of brackets. Some of these alloys also contain traces of the cytotoxic cadmium (Cd), which is added to lower the melting temperature and improve wetting. Moreover, silver-based brazing alloys form a galvanic couple that can lead to ionic release, mainly copper (Cu) and zinc (Zn). Corrosion, which has been substantially minimized in current materials, is the main reason for the progressive dissolution of brazing filler metal, leading to detachment of the wing from the bracket base during orthodontic therapy or at the debonding stage. To overcome this problem, several manufacturers have introduced gold-based brazing materials that might lead to the dissolution of stainless steel, because of the formation of the galvanic couple. Thus, although brazing alloys can facilitate the manufacturing of brackets with alloys of certain properties – e.g. a stiffer alloy for the wing to withstand the loads from activated wires and a softer alloy for the base to facilitate a peel-off effect during debonding – they have several problems.

Alloy brazing

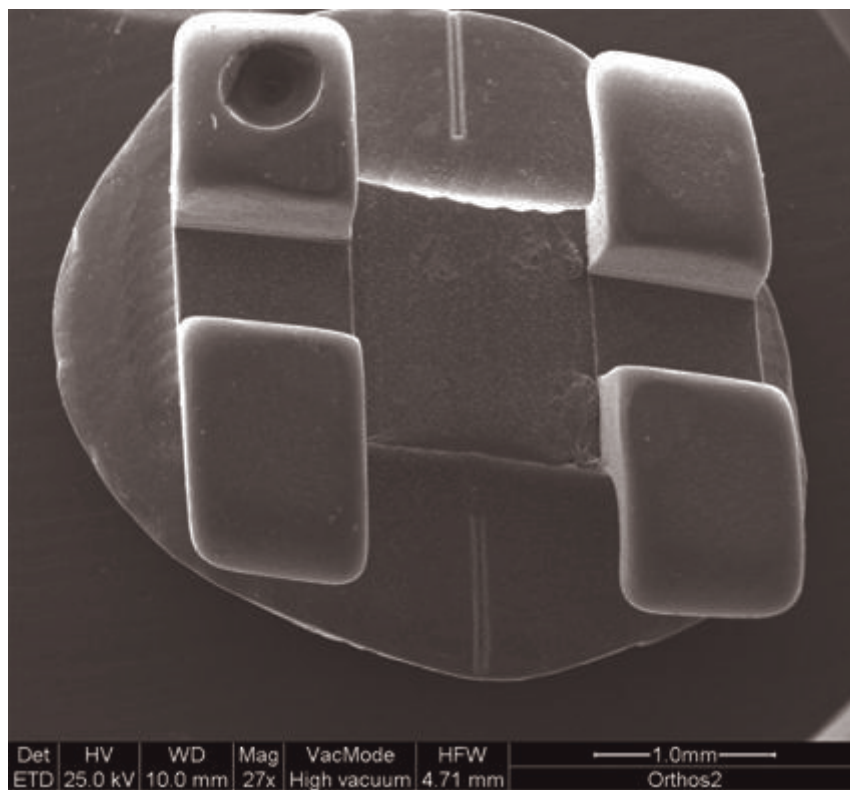
This method of fabrication involves the joint of the two basic components, namely the wings and the base as well as the attachment of mesh to the base. In the first case special brazing filler alloys are applied between the bracket base and wing interface (Fig. 2.4). The brazability of these steels may change depending on alloy composition, whereas the quality of brazed joints depends on the selection of brazing process, temperature, filler metal and the type of protective atmosphere or flux that is used.¹ Most stainless steel alloys can be brazed with any one of several different filler metal families, including silver (Ag), nickel (Ni), Cu and gold (Au)^{6–9}.

Initially, stainless steel brackets were brazed with Ag-based filler alloys, which are also the most frequently used brazing filler metal for stainless steel in industrial applications⁹. However, the orthodontic Ag brazing alloys involved the presence of Cd¹⁰ which was added to lower the melting temperature and improved wetting⁵. Moreover, Ag-based brazing alloys introduce a galvanic couple with stainless steel alloys inducing release of metallic ions with Cu and Zn the most easily leached out elements from Ag brazing alloys¹¹. Previous studies have demonstrated that brazing alloys that contained Cu and Zn had the higher cytotoxic effect among other orthodontic metallic materials¹¹. This galvanic corrosion is the main reason for the progressive dissolution of brazing filler metal leading to detachment of the wing from the bracket base during orthodontic therapy or at the debonding stage¹. Finally, almost all except two Ag-based brazing alloys are used at brazing temperature within the range of sensitizing temperatures (540–870°C) for austenitic stainless steels used for the manufacturing of base and wing components. Chromium carbide precipitation occurs in the sensitizing temperature range which impairs the corrosion resistance of the base metal.

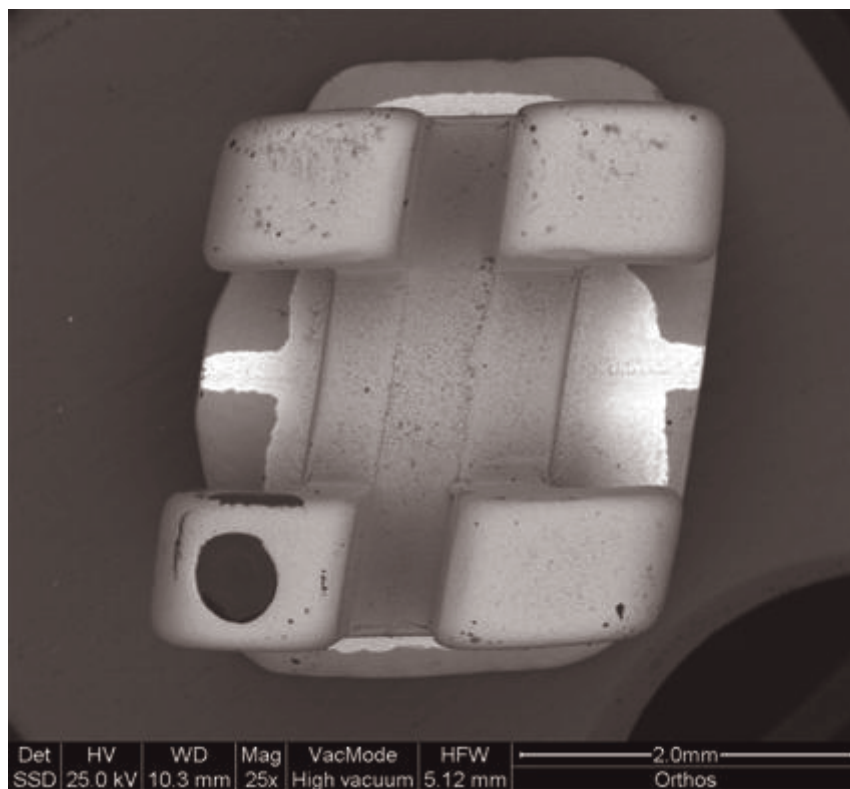
To overcome this problem several manufacturers have introduced Au-based brazing materials. However, this may lead to dissolution of stainless steel, which is less noble than the Au alloys and this may be the explanation for the *in vivo* corrosion of bracket bases¹² as well as for Ni leaching from stainless steel alloys¹³. Metal ion release from brackets and orthodontic appliances in general is of great concern regarding the adverse effects of allergic reactions or cytotoxic effects^{14,15}. The relevant literature shows a lack of evidence on this very important issue, which modulates the corrosion resistance and biological properties of orthodontic alloys.

The results of relevant studies show that manufacturers employ different alloys for brazing bracket components. Ni-based and Au-based alloys containing iron (Fe), Ni and Cr have been detected. When Au-based brazing alloys are used there is a minimal alloying with the stainless steel base metals and therefore joints exhibit good ductility, strength and corrosion resistance.

Apart from the concern of potential adverse biological effects of specific elements contained in brazing alloys, the electrochemical properties of the latter play a crucial role for the corrosion resistance



a



b

Fig. 2.4 Scanning electron microscopy images of brackets. (a) Secondary electron image of a laser welding of a two-piece appliance. (b) Back-scattered electron image of an alloy brazed, two-piece appliance. Note the formations on the left side of the image, which arise from the laser welding process and the Au brazing alloy on (b).

of the bracket^{14,15}. The galvanic couple of brazing alloy with stainless steel may lead to the progressive dissolution of the less noble alloy.

The large differences in the choice of brazing alloys imply that brazing technology has not reached a standard for bracket brazing. However, it must be noted that all the families of brazing alloys for stainless steel have comparative disadvantages for bracket brazing technology. Ag-based alloys demonstrate severe limitations, while Ni-based alloys raise serious concerns about their biocompatibility. Au-based brazing alloys are costly and there are implications for the *in vivo* dissolution of stainless steel alloys and Ni release. The selection of an optimum brazing alloy is a real challenge for the brazing technology as this material should fulfill a wide range of metallurgical, corrosion resistance and biological criteria including: (a) compatibility with stainless steel, (b) brazing cycle outside the sensitizing temperatures of stainless steel, (c) mechanical strength of jointed parts, (d) free from elements with adverse biological effects (Cd, Ni, Cu, Zn, etc.) and (e) galvanic compatibility with stainless steel alloys used for the base and wing components. It seems that there is no brazing material satisfying the foregoing requirements and, thus, development of novel brazing alloys for orthodontic applications constitutes an important area for future research.

Metal injection molding

Metallic orthodontic brackets are predominantly fabricated by casting and milling, which may also be used in combination¹. However, during the past few years a new method, metal injection molding (MIM), has been adopted for the manufacturing of metallic orthodontic brackets¹⁶. The MIM method was discovered and developed in the US in the early 1980s and is especially suitable for the production of small parts^{17,18}. In the MIM process¹⁹ metal powders with particle sizes of a few microns are mixed with organic binders (typically wax, thermoplastic resins and other materials), lubricants and dispersants, until a homogeneous mixture is obtained. Injection of the feedstock is done using an injection molding machine similar to those used in the plastics industry. The injected parts are called 'green parts' and are formed into the desired geometry but 18–

20% oversized to compensate for shrinkage after sintering. The next procedure is the 'debinding' which removes at least 90% of the organic binder from green parts by using heat, solvent or both. The 'green parts' have now been transformed into brown parts preserving the same size with a quite porous structure. The final stage of the process is sintering which is performed in a high-temperature controlled-atmosphere furnace or in a vacuum furnace. In this stage the residual binder is removed and at the end of the process the parts have shrunk by 17–22% and reached the precise desired dimensions as shrinkage is similar along the three axes. However, in some cases secondary operations such as thermal or surface treatments are required. MIM products have tight tolerances of up to $\pm 0.3\%$ of the desired dimensions and density values more than 97% of the theoretical density of the material¹⁸.

The use of new alloys for the production of MIM brackets with different mechanical properties may affect their mechanical performance under clinical conditions, while as a single piece appliance, MIM brackets will be free of corrosion consequences associated with the galvanic couple of brazing alloys with stainless steel. Despite the sufficient number of MIM brackets commercially available there is no information regarding the materials and the mechanical properties of these appliances.

Relevant studies have indicated that manufacturers employ a variety of alloys in MIM-made brackets. Although MIM may allow for the use of any alloy for the production of orthodontic brackets, the elemental composition of alloys has very serious implications for the biocompatibility, corrosion resistance and ionic release of orthodontic appliances²⁰. Brackets produced by MIM technology are actually single piece appliances and thus supposedly free from the corrosion risk associated with the galvanic couple of brazing alloys with stainless steel. However, appliances manufactured with the MIM method, have shown extended porosity, which may be assigned to the shrinkage of green parts during sintering. Although theoretically the MIM parts have a density more than 97% of the nominal value a large number of factors (alloy, powder type, debinding method, sintering heat rate, sintering hold time, etc.) may have important effects on porosity development during the manufacturing process^{21–23}. An almost uniform distribution of porosity is a

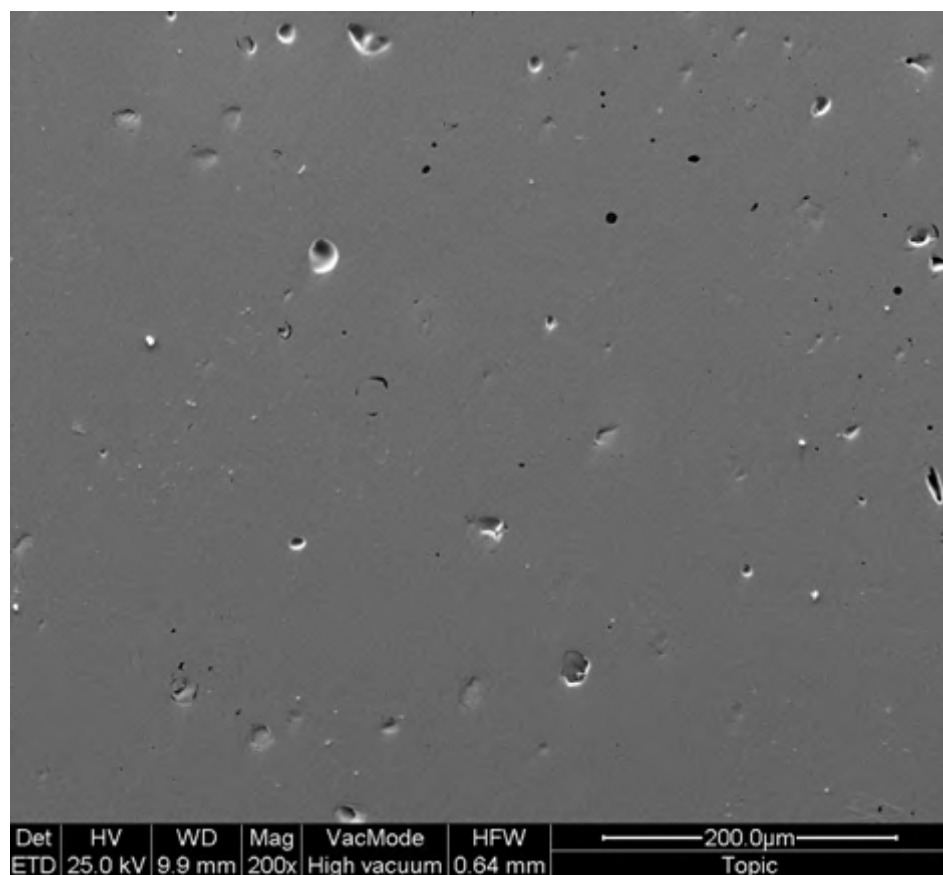


Fig. 2.5 Scanning electron microscopy image of an MIM appliance showing extended porosity.

known defect of MIM parts, and thus efforts should be focused on eliminating it, because evidence suggests that this type of porosity (Fig. 2.5) decreases the mechanical and corrosion properties of MIM products²³.

The Vickers hardness (VH) of brackets made with this method varied from 154–287 VH, which was much lower than the hardness (400 VH) of wing components of conventional stainless steel brackets¹⁶. This difference may have significant effects on the wear phenomena encountered during the archwire activation into the bracket slot. Stainless steel archwires demonstrate a hardness of 600 VH while the hardness of nickel–titanium archwires ranges from 300–430 VH. The mismatch in hardness should be minimized in order to avoid wear phenomena during orthodontic treatment. The clinical significance of hardness is that low-hardness wing components may complicate the transfer of torque from an activated archwire to the bracket as they may preclude full engagement of the wire to the slot wall

and possible plastic deformation of the wing. The use of MIM brackets with nickel–titanium archwires is recommended in order to decrease consequences of hardness mismatch.

Laser soldering and MIM

Laser welding has not been expanded and a limited number of products are fabricated with this method (Fig. 2.4). The main advantages of the method relate to the fact that whereas two alloys with different stiffness can be used, the absence of an intermediate phase and potential corrosion risk optimize the prospective performance of the final product.

BRACKET SLOT

The foregoing discussion on the integrity of wings may also be valid to the slot characteristics. In addi-

tion to high stiffness, which minimizes plastic deformation during archwire–bracket engagement, the slot must be of adequate hardness, low roughness, consistent size, shape and possess consistency in the prescribed buccal–lingual and mesial–distal inclinations^{24,25}.

Hardness, as analysed in the preceding section, is necessary to facilitate surface integrity, and preclude binding of the wire on to the bracket slot walls. The latter may affect the force levels experienced by the tooth, by increasing the friction variants, thus necessitating increase in force to achieve tooth movement. This is based on the significance of surface roughness on slot–archwire interfacial sliding during displacement of the bracket along the archwire.

Roughness indices have been proposed to provide a quantitative means of assessing the surface roughness of various materials. The most frequently used are:

- Average roughness (R_a), which describes the overall surface roughness, and can be defined as the arithmetic mean of all absolute distances of the roughness profile from the centre line within the measuring length
- Root mean square roughness (R_q), representing the height distribution relative to the mean line
- Maximum roughness depth (R_t), which registers isolated profile features on the surface
- R_z , which describes the average maximum peak-to-valley height of five consecutive sampling depths

More extended analysis of further indices and their importance in materials is beyond the scope of this chapter; the reader is referred to the vast relevant literature, which examines the variation of roughness in various alloys, ceramics and polymers.

Thus, different roughness parameters may result in different forces developed in the wire–bracket engagement surface (Fig. 2.6). For example, a slot surface of high R_z , presents a pattern which is characterized by consecutively arranged peaks and valleys. These features differentiate the force because of the effective contact between the wire and bracket. At the microscopic level, this contact is not continuous, but possesses a profile of opposing peaks arising from the variation of surfaces between the two materials coming in contact. For a given force appli-

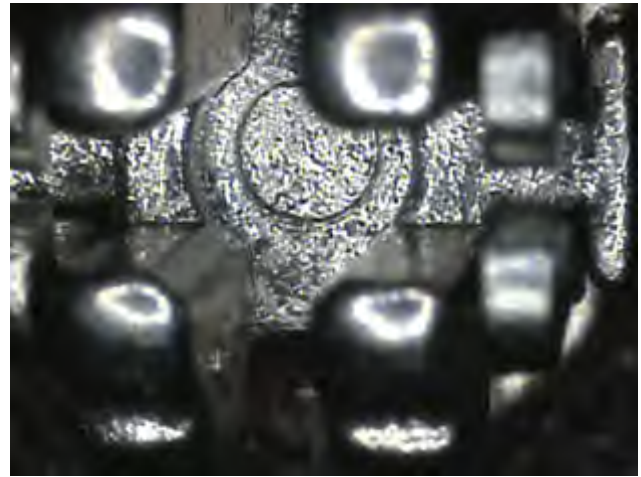


Fig. 2.6 Reflected light microscopy image illustrating the roughness of a slot.

cation and R_a , force would be much higher in the slot–wire combination which shows the least number of high peaks. Increasing the number of peaks in contact results in an increase in the surface area, and an overall decrease in the resultant pressure applied to the bracket.

Size consistency is important in ensuring that the wire engagement is properly achieved and that the prescribed torque and tip in the slot are expressed in a predictable manner. Manufacturing of brackets allows for an acceptable variation in their size and characteristics including dimensional accuracy and torque consistency. Therefore, some variability may be noted among nominally identical materials between the reported and the actual torque values. It has been shown that reported torque differs from the actual one by 5–10%, which represents roughly 1–1.5°. Various bracket manufacturing processes involving injection molding, casting or milling may also affect the accuracy of the prescribed torque values. Molding exposes the material to expansion and shrinkage, whereas milling may incorporate a rough grained surface.

Equally critical with the prescription is the size and the shape of the slot walls²⁶. Apart from the foregoing variation, the dimensional inconsistency of the bracket base and slot components may alter the bucco–lingual position of the crown; deeper slots tend to orient the crown more buccally, whereas shallower slots would probably apply a lingual orientation. Studies have revealed a variety of deviations for the reported values in slot sizes and shapes

with often divergent or convergent slot walls, which means that in many cases the wire is not fully seated inside the bracket slot or, in the case of divergent shape, the wire is fully engaged but the play is exaggerated because of the slot wall openings.

The thickness of the bracket may too have an effect on a number of properties and handling characteristics. First, it can affect the esthetics and, most importantly, the discomfort of the patient because bulky appliances are difficult to tolerate and usually are not well received by highly esthetic-conscious individuals. Moreover, these thick brackets may be subjected to higher failure rates because of the masticatory forces or development of moments during contact with opposing teeth. Nonetheless, such an effect has not been validated in the case of self-ligating brackets, which presented similar failure rates to those of conventional appliances²⁷.

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3

Biomechanics of Self-Ligation: Analysis of Forces and Moments Exerted by Self-Ligating Brackets

Nikolaos Pandis, Theodore Eliades and Christoph Bourauel

INTRODUCTION

Self-ligating brackets were introduced in clinical practice to replace the existing conventional ligation methods with elastomeric and stainless steel ligatures and improve clinical efficacy¹⁻³. Consistent archwire engagement throughout the full course of orthodontic treatment and elimination of the need for frequent visits for the replacement of ligatures were the main advantages listed for the new ligation mode⁴⁻⁵. Additionally, it was proposed that due to the bracket–wire engagement, light forces and reduced friction are attained with desirable outcome on the rate of orthodontic tooth movement. For a given cross-section and modulus of archwire, the magnitude of force developed during engagement may vary depending on the interbracket span, ligation mode and number of teeth ligated in the proximal and distal segments of the arch. This effect arises from the increased stiffness of the wire–bracket complex associated with the presence of many dental units incorporated into the mechanotherapy⁶. Additional factors which modulate force magnitude may relate to the degree of crowding, which is associated with interbracket distance, the relaxation of ligatures and clip modulus of elasticity and relaxation of self-ligating bracket engaging mechanism⁷, which may alter or modify the load transmitted to teeth⁸. Despite the emphasis placed on the necessity of applying light forces, a notable scarcity of evidence exists on the forces and moments generated during activation of an archwire in self-ligating brackets in a crowded arch^{9,10}.

In this chapter we will deal with the biomechanics of the self-ligating appliances as they compare with the conventional systems by presenting and evaluating the available scientific evidence in the current peer-reviewed orthodontic literature. The body of evidence presented originates from the work of the authors summarized in four studies, which comparatively evaluated the forces generated during simulated intrusion–extrusion, during bucco–lingual movement and the moments during rotational movements with one conventional (Orthos2, ORMCO), one passive self-ligating (Damon2, ORMCO) and one active self-ligating (In-Ovation R, GAC) bracket.

The methodology involved the construction of resin models from the original mandibular crowded arch of a patient representing a routine crowded case and the aligned mandibular model of the same patient. The force and moment measurements were performed on the Orthodontic Measurement and Simulation System (OMSS) at the University of Bonn¹¹. The major components of the OMSS system, which was custom-made for specific orthodontic applications, consist of two force-moment sensors capable of measuring forces and moments in all three planes of space, simultaneously. The two sensors of the OMSS are mounted on a motor-driven positioning table with full three-dimensional mobility, whereas all mechanical components are built in a temperature-controlled chamber, interfaced with a computer. This system is capable of performing various types of measurement, and the resultant force–deflection curves are recorded, thus facilitating a means to study the loads arising from mock orthodontic tooth movement.

FORCES GENERATED DURING INITIAL ALIGNMENT WITH SELF-LIGATING AND CONVENTIONAL BRACKETS

The first experiment¹² evaluated the forces and moments generated at different sections of the dental arch during initial archwire activation with a 0.014" copper-nickel-titanium, Damon archform wire (ORMCO) in a routine mandibular crowding case shown in Fig. 3.1.

As the wire is engaged, the lateral incisor experiences a higher force in the bucco-lingual direction



Fig. 3.1 Occlusal view of a typical crowded mandibular arch, utilized as a model for the estimation of forces on a lingually positioned lateral incisor.

because of its lingual displacement (Fig. 3.2). In Fig. 3.3 the force exerted on the same tooth is registered with the three different brackets studied, indicating a higher initial magnitude for the self-ligating Damon2 appliance.

The results of this investigation suggest that for a given archwire, there are complex bracket/archform and tooth relationships, which modulate the magnitude and direction of forces and that the increased wire-bracket free play cannot reliably predict the loads exerted by self-ligating brackets. Variations of force levels among the three brackets tested followed a complex pattern and seem to be influenced by multiple factors including ligation mechanism, bracket width, archform and tooth position, each contributing with variable weighting depending on the specific characteristics of the arch and the wire. For example, a lingually positioned, crowded mandibular lateral incisor presented an extrusive and buccal movement with the Damon2 bracket showing the lowest force in the vertical plane (intrusion-extrusion), with the self-ligating group of brackets generating the highest force in the bucco-lingual direction (Fig. 3.4).

The moments data obtained from the three brackets on the selected teeth verify the effect of direction of movement on modification of loads and moments on teeth. Whereas there is a trend for the self-ligating brackets to show decreased moments on the vertical axis for all three teeth, the rankings of moments exerted by each appliance are modified, and in some

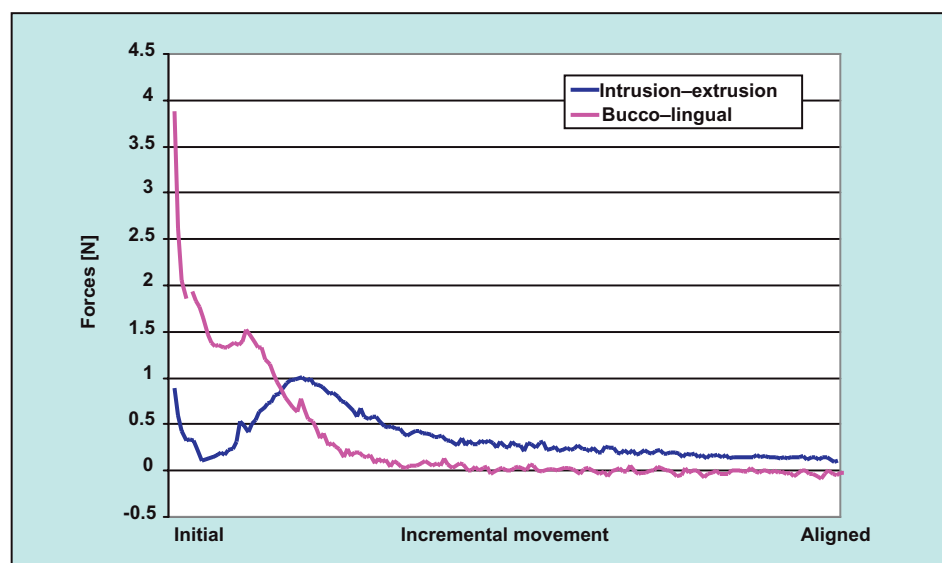


Fig. 3.2 Variation of force during engagement and alignment of the lingually positioned lateral incisor shown in Fig. 3.1. Note the higher force magnitude seen in the bucco-lingual direction, as anticipated by the misalignment of the crown in that direction.

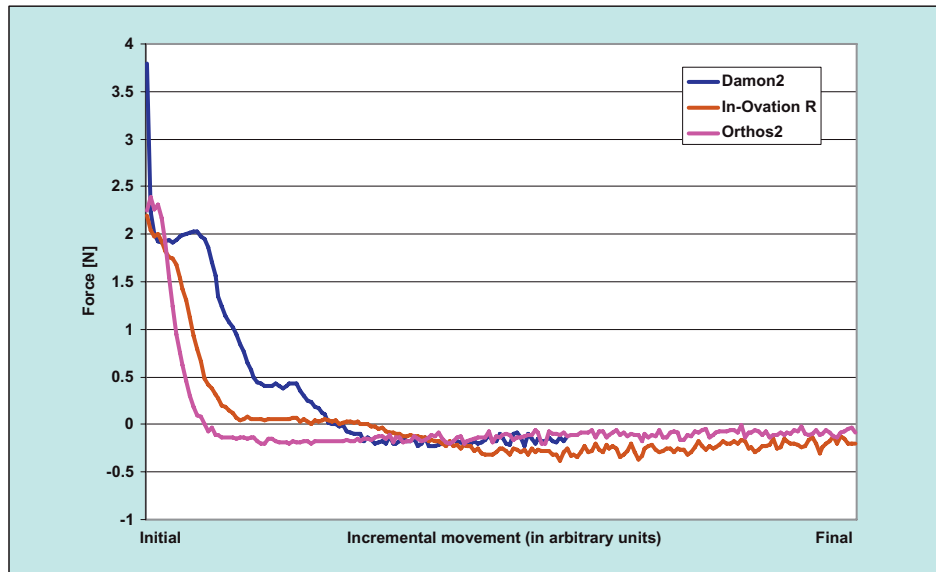


Fig. 3.3 Variation of force during engagement and alignment of the lingually positioned lateral incisor shown in Fig. 3.1, in the bucco-lingual direction with conventional, and active and passive self-ligating brackets. Note the higher force magnitude seen for the Damon2 bracket at the initial stages of wire insertion.

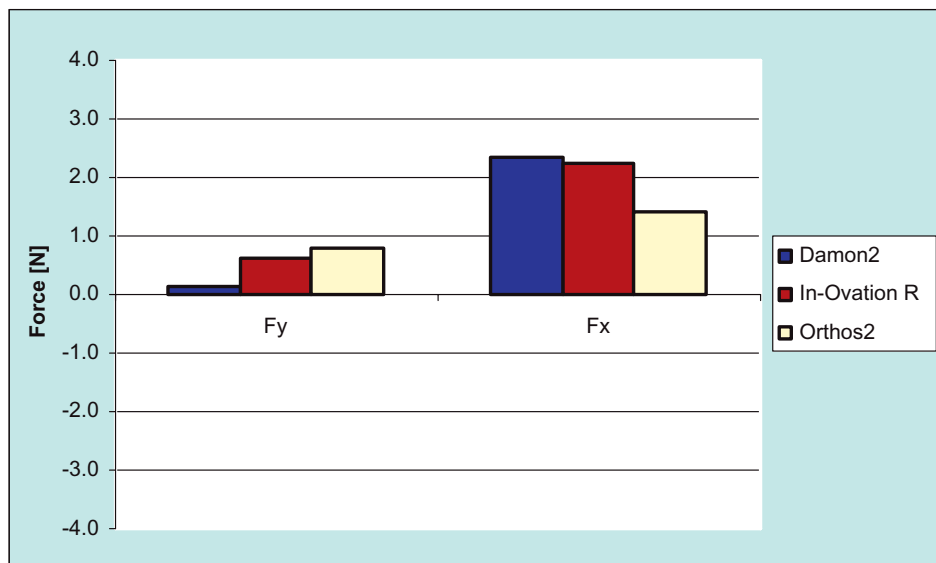


Fig. 3.4 Mean absolute forces developed at the lateral incisor position during engagement of a wire into the slots of conventional and self-ligating brackets at the vertical (F_y) and bucco-lingual (F_x) direction. Note the lower overall forces for the self-ligating brackets on the vertical direction and the reverse of the trend on the bucco-lingual direction.

cases almost reversed when the direction is changed to bucco-lingual. This variation should be assigned to the stiffness of the closing component of the slot, which, when not rigid, relaxes thereby lowering the force applied on the tooth. Whereas some of the statistical differences between values may not have clinical significance, for some movements these differences are exceedingly high. For example, the Damon2 bracket generates a moment of the crowded lateral incisor of the order of 20 N mm, when the conventional appliance shows about half of that value for the same tooth. On the contrary, in cases

where the conventional bracket shows higher moments than the self-ligating appliances, as in the case of the canine in the vertical axis, the absolute values for moments are much lower than the corresponding maxima for self-ligating brackets, i.e. 6.5 vs 19.5 N mm. Fig. 3.5 displays the absolute values (no direction denoted) of the moments generated on the vertical (M_y) and on the bucco-lingual axis (M_x – mesio-distal tipping moment).

The reduction in force levels in certain directions for self-ligating brackets may be assigned to the increased play of wires in the slot and the lack of

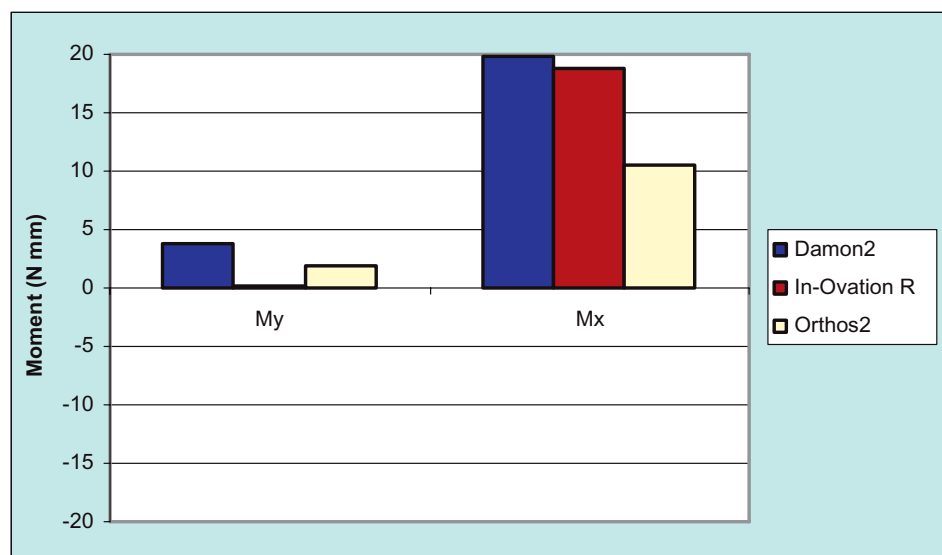


Fig. 3.5 Mean absolute moments developed at the lateral incisor position during engagement of a wire into the slots of conventional and self-ligating brackets at the vertical (My) and bucco-lingual (Mx –mesio-distal tipping) direction. Note the variability of the moments in the vertical and bucco-lingual direction, and the higher moment values generated by the Damon2 in both directions.

obstacles arising from the contact of an elastomeric ligature outside the wings. Variations in the design of the closing mechanism of self-ligating brackets (passive vs active) may affect the force generated by the displaced bracket. The rigid buccal slot wall of the Damon2 bracket may be a limiting factor, which does not allow movement of the wire as the bracket is placed lingually and the wire comes in contact with the outer slot wall. In contrast, the elastically deformed clip of the In-Ovation R bracket provides flexibility as the wire is pressed against the buccal clip. Conventional brackets do not possess this fourth wall, but the use of a new elastomeric ligature may also restrict the movement of the archwire. Additionally, aging alterations of the clip of active self-ligating brackets, occurring during the course of orthodontic treatment, may modify the forces generated during wire engagement⁷.

The results of this study imply that interbracket distance alone is not a reliable predicting factor of force magnitude during archwire engagement. This is clearly illustrated in the results found for the bracket with the least width (Damon2); this showed force levels which were lower in certain teeth and direction of movement combinations, and higher in others, implying that the effect of ligating mode prevails over interbracket distance.

Potential differences in the values reported in this study and previous investigations examining self-ligating brackets should be assigned, among other minor influences, primarily to different types of

closing mechanisms noted among self-ligating appliances, different bracket widths and varying bracket slot–archwire play. The configuration of the present experimental model examined the forces in a mandibular arch of ten teeth in contrast to the engagement of a single tooth^{13,14} in similar approaches; a fact which may greatly differentiate the forces developed.

The relevant literature lists a small number of studies examining the magnitude of forces developed during engagement of archwires into the slot of conventional and self-ligating brackets. Even fewer studies present a configuration which involves registration of forces on multiple regions in the dental arch on tooth crowns and not archwire loads. Such an investigation was reported by Kasuya *et al.*¹⁵, who measured the force levels corresponding to the unloading portion of the curve of archwires during first-order deflection of various ligation modes in lower incisor brackets mounted on metal beams, where a 0.016" nickel–titanium wire and a maximum deflection of 1500 μm were used. It was reported that ligation with elastomerics generated higher loads compared to passive self-ligation. However, the materials and the methodology included in their research are vastly different from the methodology used in the present investigation and in essence possess no clinical relevance. On the contrary, others¹⁶ using an experimental configuration resembling that used in the authors' study, incorporating a full case of brackets and 0.014"

nickel–titanium archwire, found greater variability among the different brackets with regard to the unloading forces. Moreover, in specific areas of the arch, the unloading forces recorded were higher for the passive self-ligating brackets; a finding which is in agreement with the data presented in the authors' study.

FORCES GENERATED BY CONVENTIONAL AND SELF-LIGATING BRACKETS DURING SIMULATED INTRUSION–EXTRUSION AND BUCCO-LINGUAL CORRECTION

This section takes a step further in assessing the force generated by the engagement of wire into the bracket slot, in that it summarizes evidence from a study¹⁷ which estimated the force levels as a function of displacement at two directions, i.e. bucco-lingual and intrusion–extrusion forces, corresponding to the in–out and upward–downward movement of teeth. Fig. 3.6 depicts the set-up on the OMSS for this purpose, which shows the system at minimum and maximum displacement.

Forces were recorded after a 0.014×0.025 copper–nickel–titanium Damon archform archwire was tied in the brackets bonded to a model constructed of a patient in the late alignment stages of treatment. The specific range of displacement utilized in the experiment was confined to 2 mm in the vertical dimension and 1 mm in the in–out direction because at the time of wire insertion, it is expected that initial leveling and aligning would have probably eliminated variation in crown spatial orientation relative to the archform.

Overall the results show similar force/deflection curves, which seem to be dominated by the characteristics of the wire. In the intrusion–extrusion movement (Fig. 3.7a), the direction of displacement does not affect the level of force exerted by any of the bracket systems tested, probably due to the irrelevance of the bracket design with the forces generated; these are applied on the incisal and gingival walls of the slot, which do not show a remarkable variation among the three brackets tested. In this model, self-ligating brackets seem to exert lower forces (5.7, 5.8 N) compared to the conventionally ligated brackets (6.7 N) (Fig. 3.7b). This drop in force levels may be assigned to the increased play of

wires in the slot and the lack of obstacles arising from the contact of an elastomeric ligature outside the wings. The difference, however, accounts for 1 N or 20% of that observed with self-ligating brackets and, therefore, the clinical significance of this observation requires further investigation.

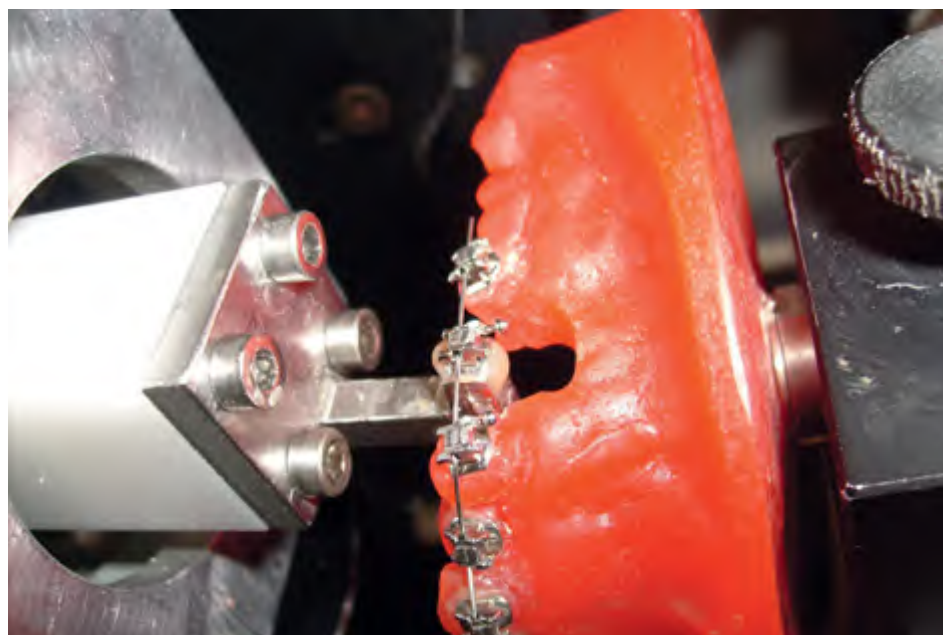
In the bucco-lingual model, however, additional factors may govern force application by the engaged archwire (Fig. 3.8). Variations in the design of the closing mechanism of the two self-ligating brackets may affect the force generated by the displaced bracket because force direction on the lingual movement of the bracket coincides with the compliant section of bracket slot. In this model, the active self-ligating bracket displayed an almost 40% reduction of the force magnitude compared to the other brackets (Fig. 3.8b). This favorable response was eliminated when the direction of displacement is reversed to the buccal (outward) movement (Fig. 3.8a). In this direction, the role of the closing segment of the slot in the self-ligating brackets possesses no importance because the wire is pressed against the rigid lingual slot wall.

The magnitude of force developed during engagement may also vary depending on the number of teeth ligated in the proximal and distal segments of the arch⁶. This effect arises from the increased stiffness of the wire–bracket complex associated with the presence of many dental units incorporated into the mechanotherapy.

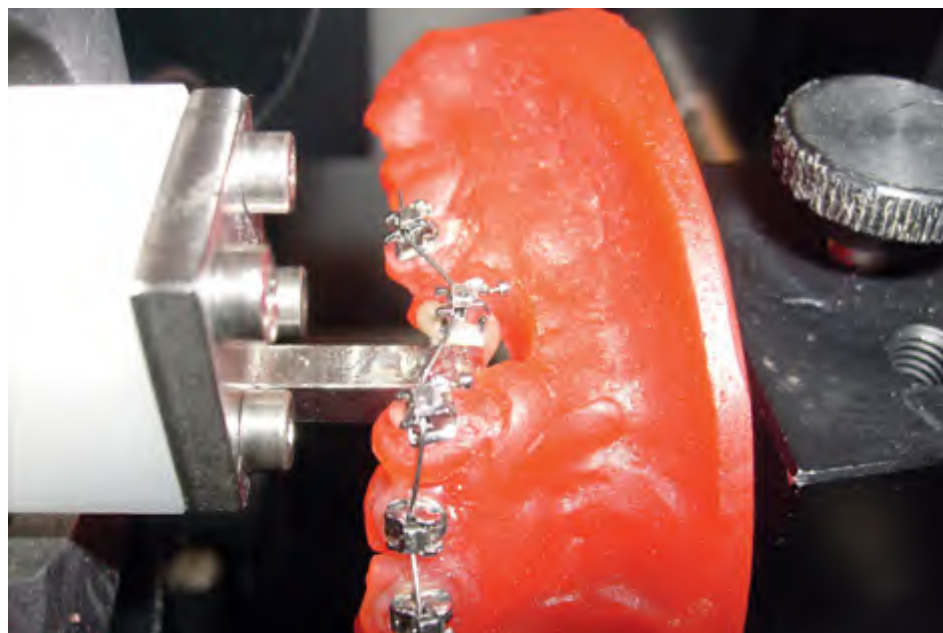
MOMENTS GENERATED DURING SIMULATED ROTATIONAL CORRECTION WITH SELF-LIGATING AND CONVENTIONAL BRACKETS

Correction of axial variation of teeth requires a moment applied to the bracket to initiate a rotational movement. Bracket width may affect moment development during axial rotations since the moment of the rotational couple is equal to the ligation force applied multiplied by the effective attachment width, and thus wider appliances, in general, produce higher moments^{9,10}.

The moments produced during simulated rotational correction from different bracket systems were assessed in a subsequent study¹⁸. As previously reported, a 0.014×0.025 copper–nickel–titanium Damon archform archwire was used on the aligned



a



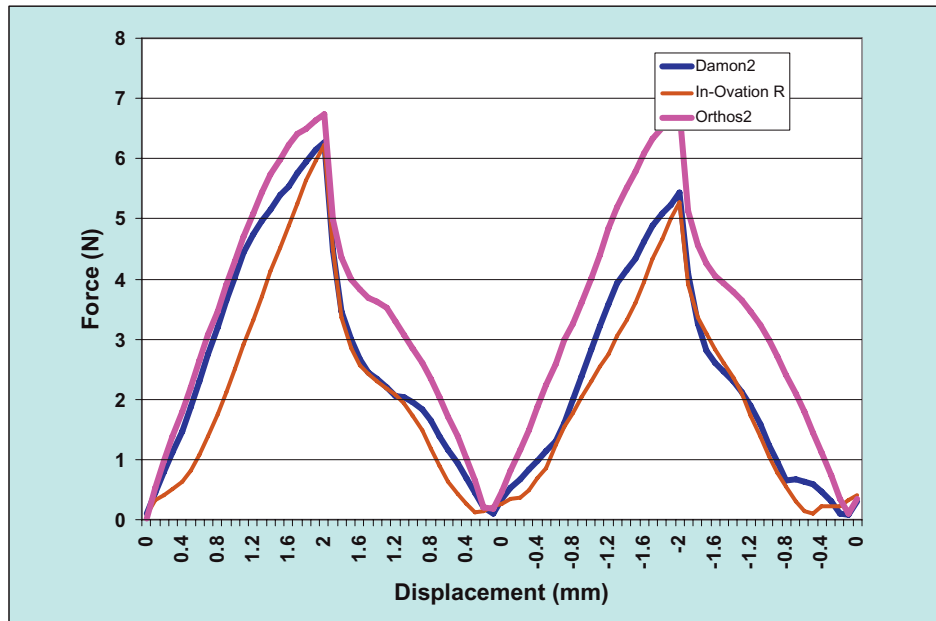
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Fig. 3.6 A model mounted on the OMSS in a configuration that allows the assessment of the force exerted on the premolar in the intrusion–extrusion direction, in equilibrium (a) and at vertical displacement (intrusion) (b).

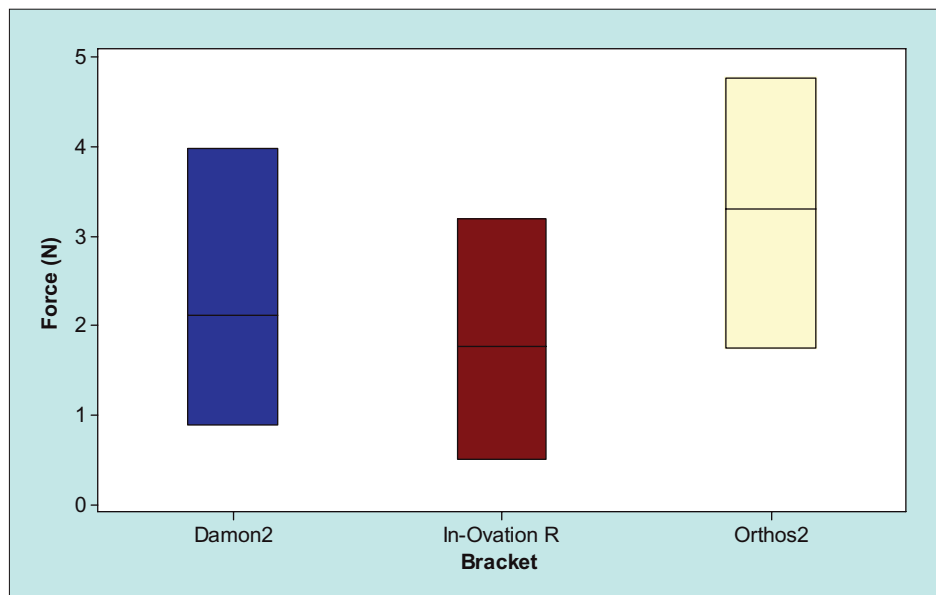
acrylic mandibular model. The specific range of displacement utilized in the experiment was confined to a range of 0° to 5° in the mesial and 0° to 5° in the distal direction because at the time of wire insertion, it is expected that initial leveling and aligning would probably have eliminated variation in crown spatial orientation relative to the arch form.

The results of that study indicated highest values for the Damon2 brackets (Fig. 3.9a); specifically, the

moments developed were more than 100% greater relative to its counterparts in this study (Fig. 3.9b). Also, higher magnitude of moments developed in the opposite direction of the higher number of teeth engaged into the archwire. Also, the direction of the premolar rotation (distal or mesial), which was used as a model, was found to exert a significant effect on the magnitude of the generated moments. This may be assigned to the number of teeth incorporated



a



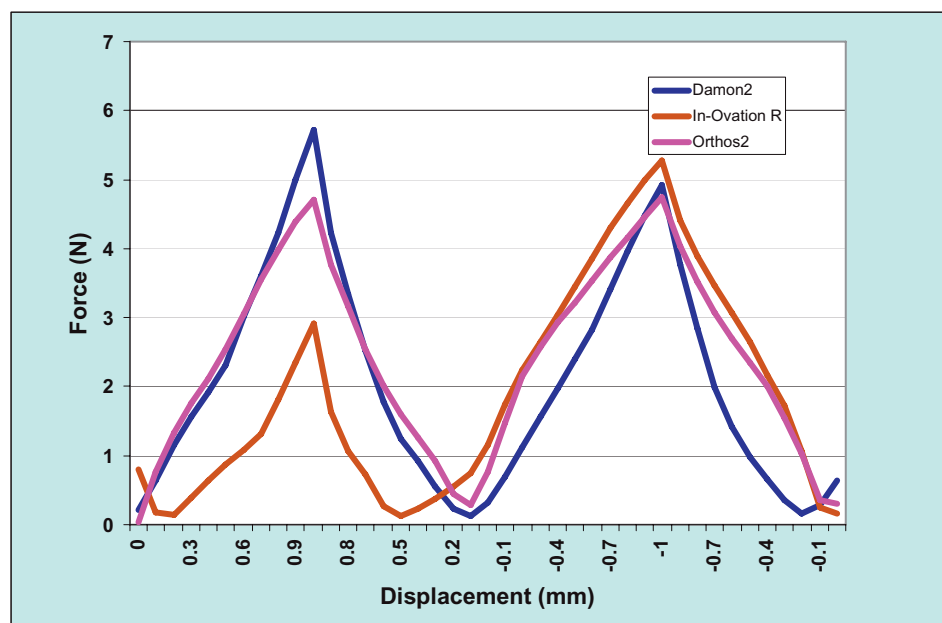
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Fig. 3.7 (a) Variation of mean force per displacement increment in intrusion–extrusion direction (intrusion is denoted by negative values). Results represent a complete loading–unloading cycle for each direction. Note the consistently increased level for conventional Orthos2 brackets, relative to the self-ligating appliances, which is direction-independent. (b) Maximum values during intrusion–extrusion recorded for conventional and self-ligating brackets.

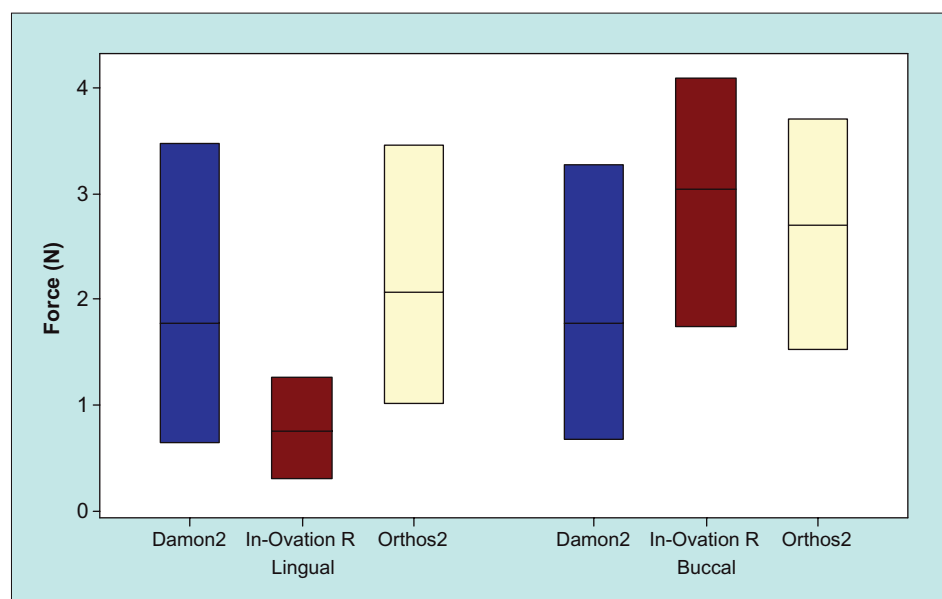
in the mechanotherapy, mesially or distally to the arch location where the sensor was inserted¹⁴.

The increased magnitude of moments formed by the Damon2 bracket could be attributed to the rigidity of the closing component of the slot, which limits the available space for the wire to move and dissipate some of the energy given at engagement (Fig. 3.10a). Although this slot wall allows for increased play when small diameter wires are inserted into the slot, its rigidity and lack of deformability results in

higher loads developed during rectangular wire engagement. This is in contrast with the case of the In-Ovation R bracket (Fig. 3.10b), which features an elastically deformed clip, which is compliant allowing more outward movement of the wire from the bottom of the slot. The same occurs with conventional brackets owing to the deformation of the elastomeric ligatures, which show more relaxation compared to the clip of the In-Ovation R bracket (Fig. 3.10c). Although this study examined the



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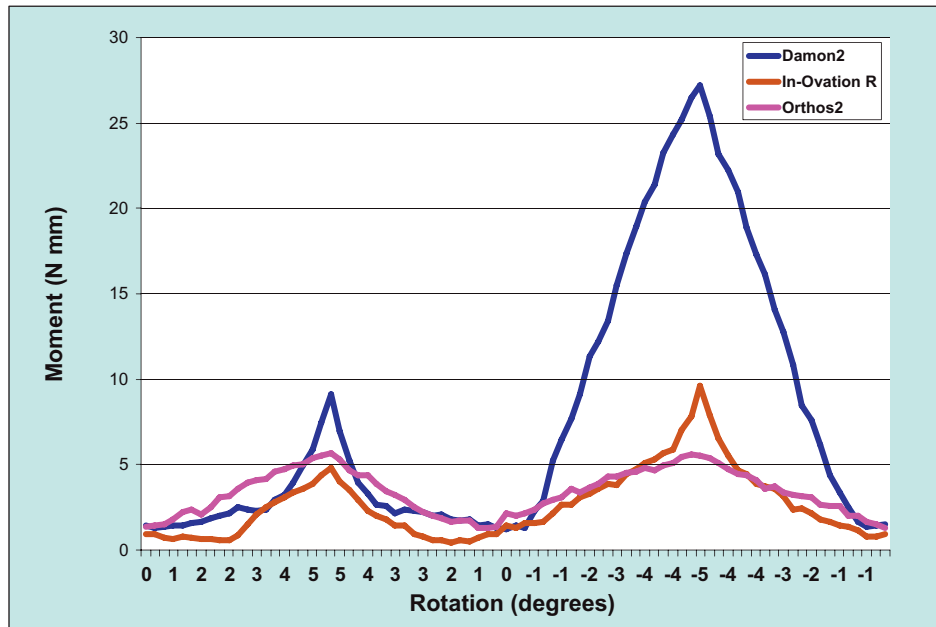


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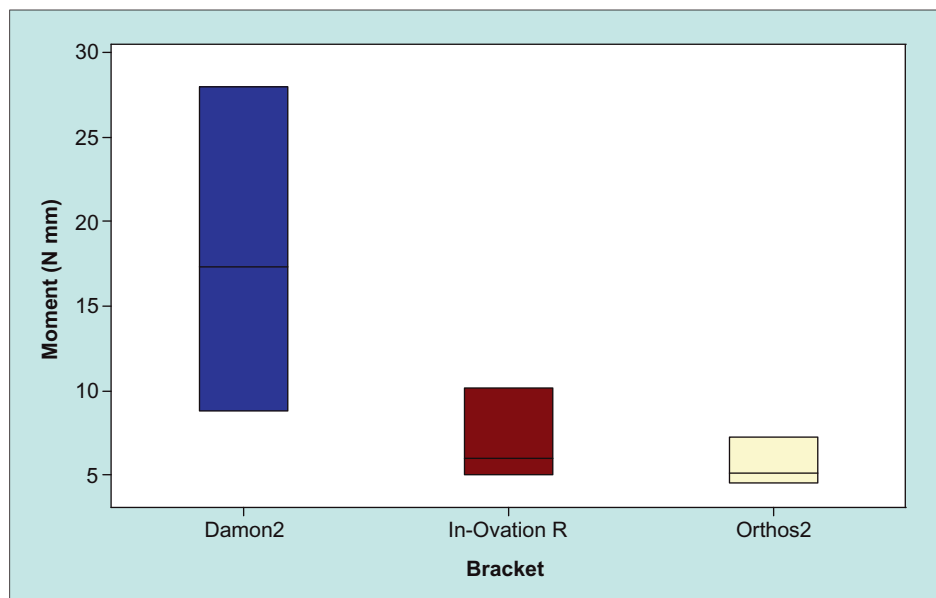
Fig. 3.8 (a) Variation of mean force per displacement increment in the bucco-lingual direction (outward or buccal direction is denoted by negative sign). Results represent a complete loading–unloading cycle for each direction. Note the decreased force exerted by the In-Ovation R bracket for the same displacement in the reverse direction arising from the compliance of the closing mechanism. (b) Maximum force values recorded for the bucco-lingual movement for conventional and self-ligating brackets.

maximum magnitude of moments developed during the applied rotation of 5° , no information can be revealed for the efficacy of bracket to apply a steady derotational moment. This concern is particularly relevant to elastomeric modules since these polyurethane-based elastomers have been found to lose approximately 50% of the force applied within the first 24 hours in an *in vitro* set-up¹⁹. More decay is expected in the oral environment because of the severity of conditions existing in the presence of pH fluctuations, temperature variations, enzyme action

and mechanical loading. Thus their use as a ligating medium in rotational movement has been questioned and stainless steel ligatures have been suggested for more efficient and consistent engagement. However, conventional ligation offers the advantage of modulating the extent of ligation by using elastomers in figure-of-eight configurations, or using stainless steel ligatures with varying degrees of tie-in force. The use of the latter nonetheless is associated with the development of higher moments, which may exceed the biological range¹⁶.



a



b

Fig. 3.9 (a) Variation of magnitude of force per rotation increment. Note that higher moments are associated with specific direction of rotation, which coincides with distal rotation, towards the arch segment where less teeth are engaged (denoted by negative values). For both directions, the Damon2 bracket showed higher moments relative to the conventional one. (b) Maximum moment values recorded for the rotational movement for conventional and self-ligating brackets.

The In-Ovation R bracket presented higher values in the distal rotation compared to the conventional one; however, this difference was eliminated when the direction was set to that of more teeth engaged or smaller interbracket distance. This behavior may be attributed to the limits of clip displacement as determined by the outer bracket wing borders and the properties of the clip. The clip responds immediately at low loads showing a compliant character, but when the deformation of the closing mechanism

exceeds a certain value, it becomes stiffer to avoid buccal movement of the archwire.

CONSISTENCY IN THE LIGATION FORCE WITH ACTIVE SELF-LIGATING BRACKETS THROUGHOUT TREATMENT

The variability of the clip stiffness in active self-ligating brackets may adversely affect consistency in



a



b



c

Fig. 3.10 (a) Engagement of wire into a Damon2 bracket slot of a rotated tooth; the stiff, inelastic closure of the fourth bracket slot wall, which may lead to increased moment production during derotation. (b) Engagement of a wire into an In-Ovation R bracket slot of a rotated tooth. The elastic properties of the clip allow for reduced moment generation. (c) Engagement of a wire into a conventional bracket slot with the use of elastomeric ligatures. The reduced stiffness of elastomer may cause incomplete engagement thereby reducing efficiency; however, moment production is also decreased.

engagement of brackets. It has been shown that the oral environment imposes a severe aging profile on the mechanical properties and surface conformation of a wide array of materials ranging from alloys to polymers and ceramics, which can adversely affect the ligating mechanism²¹.

The fourth study⁷ investigated the effect of intra-oral exposure on the alteration of stiffness of ligating mechanism of brackets, which may result in a loss of engagement force over time. This was investigated by evaluating the mechanical properties of the clip of active self-ligating brackets in the as-received and following active service in the oral cavity of patients for the full term of treatment; the fundamental question pertained to the ability of active self-ligating brackets to exert consistent force on ligated archwire throughout the full term of treatment. Although this is a basic clinical question, the design to study this parameter is biomechanically complex and relies on the estimation of the

stiffness of the clip and its variation with time. The two active self-ligating brackets included in this study were the SPEED (Strite Industries) and the In-Ovation R.

The results of this research suggest that the clips of both bracket types were not plastically deformed. However, the active clip of the one bracket displayed a significant aging effect, producing a change of mean stiffness by more than 50% (Fig. 3.11). Thus the performance and aging of the nickel–titanium clips significantly depend on the alloy composition and the associated phase transformations.

The clinical relevance of findings may relate to the inability of the relaxed clip to apply forces due to aging, which may have been imposed by the mechanical loading and environmental conditions. As a result, inadequate engagement of the wire into the bracket slot may arise in the last stages of treatment when rectangular wires are inserted, with undesirable outcome on associated mechanotherapeutical

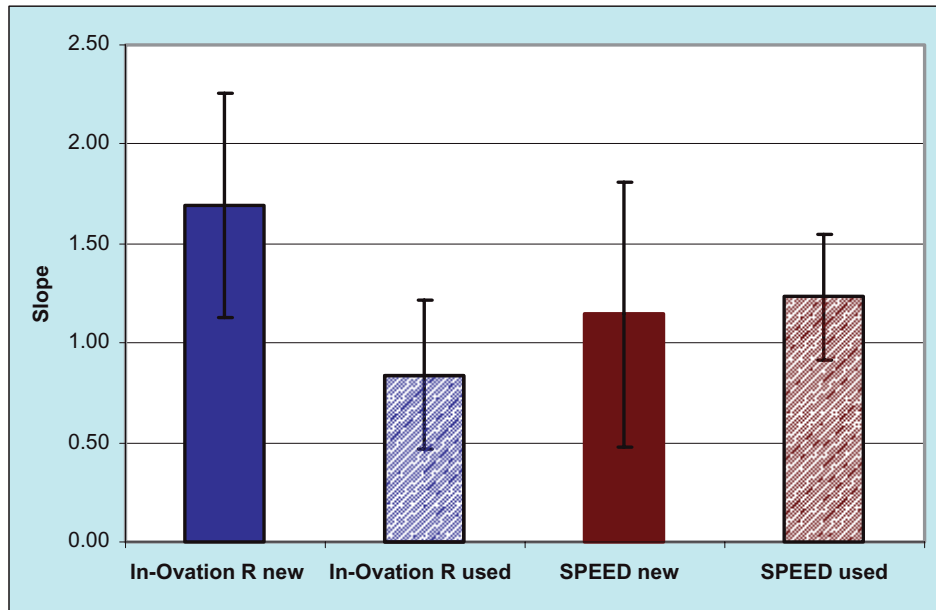


Fig. 3.11 Mean stiffness of two active self-ligating brackets before and after 18 months of use. Note the decrease in stiffness for the In-Ovation R used appliance.

schemes. The assessment of the impact of these changes requires comparative clinical studies investigating the clinical performance of these appliances.

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TREATMENT OUTCOME – CLINICAL PERFORMANCE

4

Essentials of Clinical Research Design

Argy Polychronopoulou

INTRODUCTION

Epidemiology is ‘the study of the distribution and determinants of disease frequency’¹. Clinical epidemiology is the study of illness outcomes in persons seen by healthcare providers², whereas well designed epidemiological research is the fundamental basis for sound clinical care. This chapter aims to address key issues related to the design of clinical epidemiological studies as they apply to orthodontic research. An effort is made to deal with the design of studies that may be implemented to elucidate research questions related to self-ligating appliances^{3–13}.

STUDY DESIGN

Clinical research includes non-experimental and experimental designs which investigate the etiology of a disease or evaluate a preventive/therapeutic measure through documentation of the probable association on an individual basis. Regardless of the study design two basic principles are followed: (a) a comparison between two groups and (b) elimination of all potential causes of bias¹⁴.

In non-experimental (observational) studies, the researchers observe study participants, indicating that the data are collected simply to see what is happening; whereas in experimental studies, the investigator allocates the type of intervention to the participants. Non-experimental studies are further classified as cohort studies and case-control studies^{15,16}. Fig. 4.1 schematically presents the categorization of clinical studies, and Table 4.1 presents examples of clinical orthodontic studies related to self-ligating appliances.

The basic characteristics of epidemiological studies are presented in the following sections with greater emphasis placed on experimental studies which, currently, constitute the gold standard in clinical treatment effectiveness research.

NON-EXPERIMENTAL/OBSERVATIONAL STUDIES

Cohort studies

Cohort studies are also called follow-up studies, longitudinal studies or incidence studies. Individuals are followed over a time period and their health outcome is monitored. The selection of the individuals included in the study is based on whether or not they have been exposed to the factor being investigated. These groups are defined as study cohorts, and all participants must be at risk of developing the outcome. The individuals of the study are followed for a set period of time (usually long) and all the new cases of the outcome being studied are identified. Comparisons of outcome experiences are made within the study cohorts (Fig. 4.2)^{15,17,18}.

The choice of the exposed group depends on the etiological hypothesis, the exposure frequency, and the practical difficulties of the clinical study, such as record availability or ease of follow-up. The non-exposed group provides information on the incidence of the outcome that would be expected in the exposed group, if the exposure/factor being studied did not influence the frequency of the outcome. Therefore, the non-exposed group is chosen in such a way as to secure similarity with the exposed group, in regard to the other risk factors of the outcome being studied. It follows that, ideally, the exposure

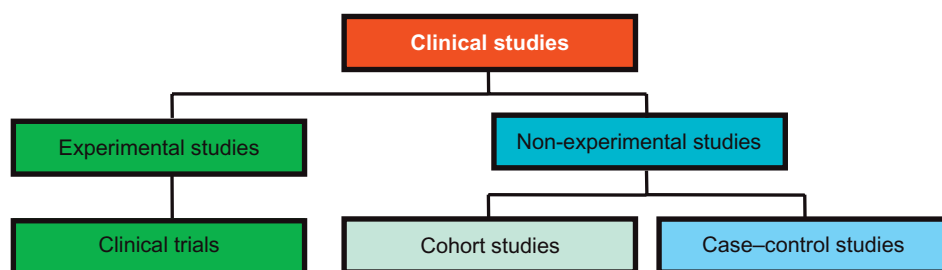


Fig. 4.1 Types of clinical studies.

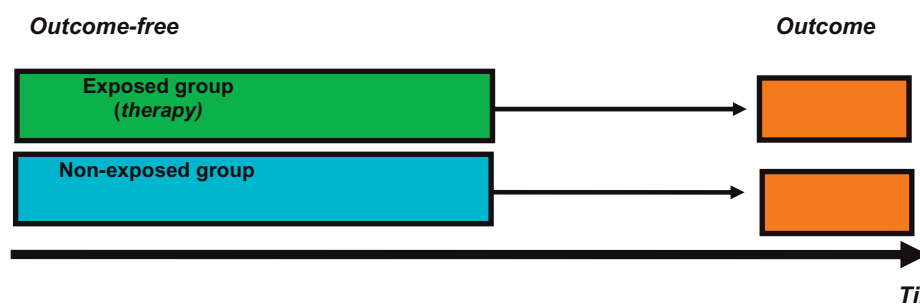


Fig. 4.2 Design of a cohort study.

Table 4.1 Examples of clinical studies investigating self-ligating brackets.

Study type		Treatment	Outcome	Source
Experimental	Randomized clinical trial	Self-ligating vs conventional brackets <i>Initial alignment</i>	Discomfort	Scott P <i>et al.</i> , 2008 ¹³
	Randomized clinical trial	Self-ligating vs conventional brackets	Duration of crowding alleviation	Pandis N <i>et al.</i> , 2007 ¹¹
Observational	Cohort	Self-ligating vs conventional brackets <i>Wire size and material</i>	Arch-wire ligation time	Turnbull NR, Birnie DJ, 2007 ¹²
	Case-control	Self-ligating vs conventional brackets	Treatment efficiency	Harradine HNW, 2001 ⁵

factor would be the only difference between the populations to be compared.

The cohort studies that are based on information on the exposure and the outcome that has been collected from pre-existing sources in the past are called *retrospective cohort studies* (Fig. 4.3). The authenticity, however, of such a study depends on the thoroughness of the certification of the outcome in the medical/dental records of the population and for the time period this is studied. Moreover, information on the relative confounding factors may not be available from such sources.

Advantages of cohort studies

In summary, these studies:

- Provide direct information on the sequence of events; thus, the temporal relationship between

exposure and outcome can be more easily elucidated

- Are optimal for the investigation of multiple effects of an exposure/treatment as long as the researcher records all the effects during the follow-up
- Allow direct measurement of incidence rates or risks and their differences and ratios

Disadvantages of cohort studies

- Prospective cohort studies can be expensive and time consuming, whereas retrospective cohort studies require the availability of adequate records
- The validity of this design can be threatened by losses to follow-up

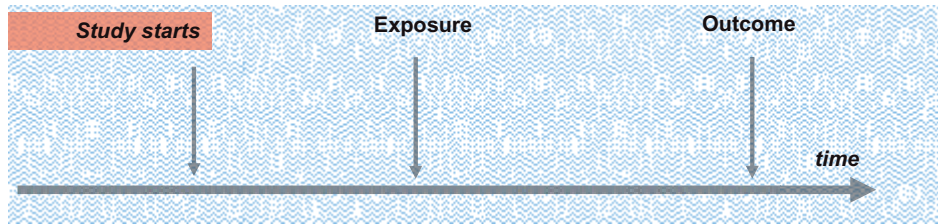
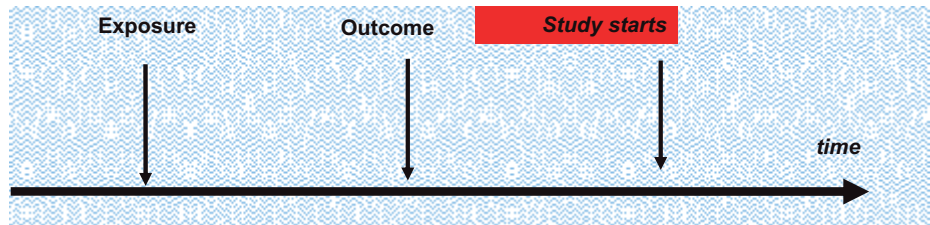
Prospective cohort**Retrospective cohort**

Fig. 4.3 Prospective and retrospective cohort study design.

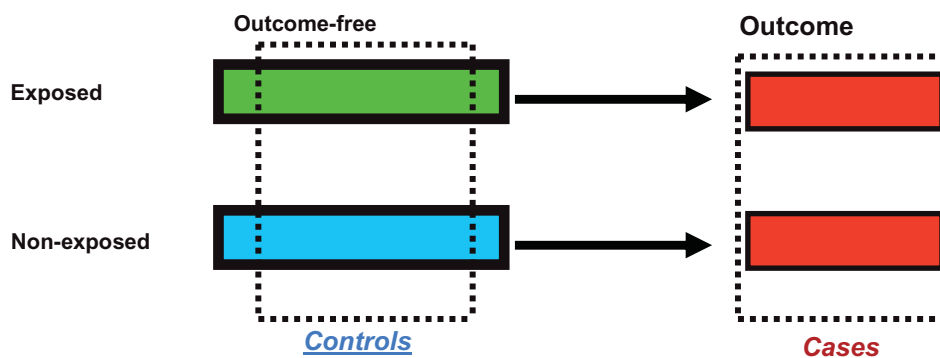


Fig. 4.4 Design of a case-control study.

- Cohort studies are not suitable for rare outcomes

Case-control studies

This design aims at achieving the same goal as the cohort study more efficiently using sampling. Controls free from the particular factor or disease are chosen as a representative sample. Ideally, the control group represents the exposure distribution in the source population that produced the cases. Subsequently, exposure information is collected both for the cases and for the controls. Data are analysed to determine whether exposure patterns are different between cases and controls (Fig. 4.4)^{15,17,19}.

The basic characteristics of case-control type studies are that the selection of individuals is made

based on the criterion that they do or do not have the disease under investigation. There are many potential sources of cases, such as those derived from private practices, clinics, hospitals, disease registries or through screening programs. For causal research, incident disease cases rather than prevalent disease cases are preferred. Incidence is the number of cases developing the disease in the total time experienced for the subjects followed; prevalence is the proportion of people in the population that has the disease. Basic criteria in the choice of the group of cases are that they must constitute a relatively homogeneous group from an etiological point of view and the facts about the disease must come from reliable sources. In that case, a sample of the population that represents the cases and provides the background exposure expected in the case group serves as a control. In many studies, the use of more than

one control group is necessary. Several sources are available for identifying controls including the general population (using random sampling), hospitals, clinics, practice-based controls, relatives and friends of cases. Persons with disease known or suspected to be related to the exposure under investigation should be excluded from being used as controls.

Advantages of case-control studies

- Case-control studies are less costly and easier to conduct than cohort or experimental studies and are the method of choice for investigating rare diseases
- Case-control studies offer the opportunity to investigate multiple etiological factors simultaneously
- Case-control studies usually require a much smaller sample than do equivalent cohort studies

Disadvantages of case-control studies

- Case-control studies do not involve a time sequence and in some situations, the temporal relationship between exposure and disease may be difficult to establish
- Case-control studies are not efficient designs for the evaluation of a rare exposure unless the study is very large or the exposure is common among those with the disease
- Incidence rates of disease in exposed and non-exposed individuals cannot be estimated in most instances
- Case-control studies are very prone to selection and recall bias

Table 4.2 summarizes the main characteristics of the subcategories of observational studies.

EXPERIMENTAL STUDIES/INTERVENTION STUDIES

Intervention studies, commonly known as clinical trials, are experimental investigations of the cohort type, where the researcher assigns the exposure to study subjects. They differ from non-experimental studies in that the condition under which the study takes place is controlled. The aim of clinical trials is

Table 4.2 Main characteristics of cohort and case-control studies.

Characteristic	Cohort studies	Case-control studies
Outcome	Unsuitable for rare outcome	Suitable for rare outcome Suitable for outcomes with long induction
Exposure	Efficient for rare exposures Good information on exposures	Can evaluate multiple exposures in relation to an outcome
Bias	Less vulnerable to bias	More vulnerable to bias: recall bias and selection bias
Time	Time consuming	Less time consuming
Cost	Expensive	Less expensive

to investigate a potential cure for disease or the prevention of a sequel^{16,20}.

Clinical trials are almost always the best way of assessing a new treatment. In the case of self-ligating appliances, these studies could be generally characterized as clinical trials exploring the efficacy of a dental device. Clinical trials involving skill-dependent activities like devices (device trials) in most aspects resemble clinical trials employing drugs (drug trials); however, devices show less of a need for extensive developmental testing compared with drugs in humans, but not less rigorous testing overall. All clinical trials, like device trials, share common core design features that are described below.

Study cohort

The individuals who participate in this type of study derive from a more general group, for which the results of the intended research would be applied; this group is called a target population. Once those who cannot participate in the study are excluded, those remaining, who are all likely candidates for the study, make up the experimental population; those subjects unwilling to give consent should be removed. The eligible and willing subjects are then allocated into two main groups: (a) basic-intervention/experiment group and (b) comparison/control group. The study subjects are followed for a specified period of time under strict conditions and the

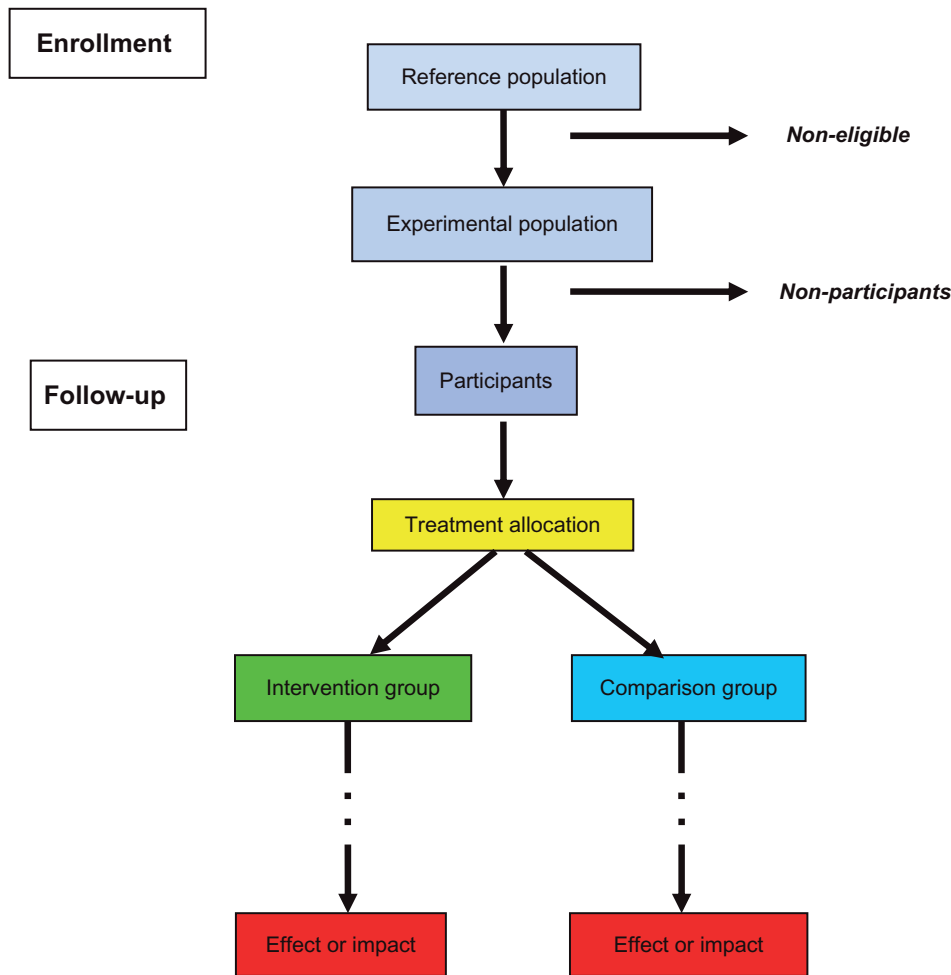


Fig. 4.5 Flowchart of a clinical trial.

effects/outcomes are carefully documented and compared between the groups. Fig. 4.5 presents a flowchart of a clinical trial. Furthermore, intervention studies can be subcategorized in many ways depending on their design and purpose (Table 4.3).

Randomization

In non-experimental clinical research (cohort and case-control), the known confounding factors may be monitored either by choice of the compared groups, or during the analysis of the data, but there is no practical way to control the unknown confounding factors. On the contrary, in experimental research, it is possible to methodologically check both the known and the unknown confounding factors with the application of randomization.

Table 4.3 Subcategories of intervention studies.

Subcategory	Characteristics
Single site	Treatment provided by a single center
Multi-site	Treatment provided by multiple coordinated centers
Preventive	Prophylactic agent is provided to prevent outcome occurrence
Therapeutic	Therapy is provided to improve survival, improve a condition
Parallel	Everyone within a group receives the same treatment which is different from the treatment given to other group
Cross-over	Each treatment is given at different times to each subject
Simple	Each group gets one treatment
Factorial	Each group gets more than one treatment

Especially in therapeutics research which includes self-ligating appliance clinical research, a complex problem is confounding by indication. Confounding by indication is a bias that results from inherent differences in prognosis between patients given different therapies. With randomization, each study subject has the same probability of receiving or not receiving the measure being studied. Thus, randomization of treatment allocation, if done properly, reduces the risk that unknown confounders will be seriously unbalanced in the study groups. Random treatment assignment ensures that prognostic factors are balanced between groups receiving the different treatments, thus baseline characteristics are equally distributed among study groups receiving different therapies. When this is done, the clinical study is characterized as a randomized controlled trial (RCT)^{16,21,22}.

Simple techniques are used for the achievement of randomization, e.g. flip of a coin, use of random number tables, or computer random number generators. Researchers use two more techniques with randomization, namely stratification and blocking, in order to achieve balanced study groups¹⁷. In stratified randomization, the study population is first separated according to the possible confounding variable and then randomized to treatment groups within each stratum (Fig. 4.6). In blocking, randomization is conducted in blocks of a certain size in

order to ensure balance with regard to the time of enrollment.

Although randomization should distribute factors evenly, this cannot be certain in all cases, especially in small trials. Success of random allocation has to be confirmed by comparing the distribution of all confounding variables at the beginning of the study. In case of noticeable differences between the two groups, further adjustments should be made when conducting the statistical comparison of outcome measures.

Blinding or masking

The reliability of such a study can, to a large degree, be influenced by the fact that the participants and the researcher know the group that the members of the study belong to and, thus, knowledge of the treatment might influence the evaluation of the outcome. The solution, then, is blinding^{16,17}. It should be noted that although blinding is desirable, however, it is not always feasible or necessary. The absence of blinding does not especially affect the results if the outcome being studied is objectively defined.

Three types of blinding exist: (a) simple blinding, where the person assessing the outcome, i.e. the orthodontist, the dentist or the assistant, knows the

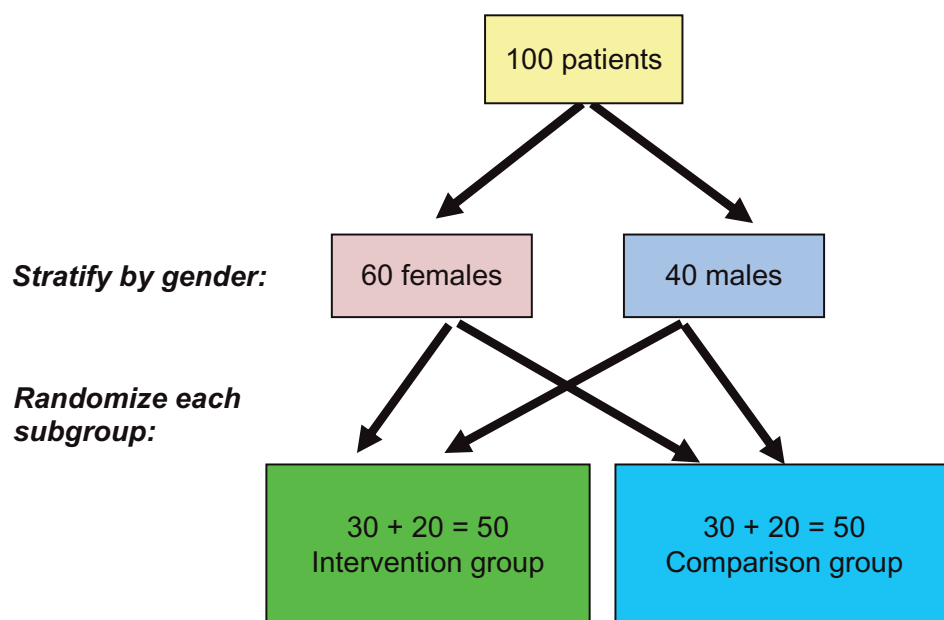


Fig. 4.6 Stratified randomization. Participants are first divided into strata according to the prognostic factor and then randomized separately within each stratum into intervention/therapy and comparison groups.

Table 4.4 Overview of the various types of blinding used in randomized clinical trials. (✓: blinded with respect to subject's allocation; –: may be aware of subject's allocation)

	Type of blinding		
	Single	Double	Triple
Participant	✓	✓	✓
Evaluator	–	✓	✓
Data analyst	–	–	✓

assigned treatment while the participant does not; (b) double blinding, where neither the evaluator, nor the participant know; and (c) triple blinding, where neither the evaluator, the participant nor the person interpreting the set of results know, which treatment has been assigned (Table 4.4).

Placebo treatment for the comparison group is often used to facilitate blinding. The placebo is inactive and morphologically similar to the therapeutic or preventive measure applied to the comparison group. When intervention studies involve procedures/devices rather than pills, sham procedures/devices take place to match the experience of the treatment and comparison groups as closely as possible. The beneficial effect produced by an inactive pill or sham procedure/device is reported as the placebo effect and is attributed to the power of suggestion. It should be noted that, for ethical reasons, if an accepted therapeutic treatment exists, then new treatments must be tested against the current best treatment and not against a placebo¹⁶.

Sample size

Sample size determination is a crucial part of any clinical trial. Several intervention studies have reported lack of association due to small sample size and low power to detect clinically important differences²³. In trials investigating device efficacy, sample size estimates depend on the particular test statistic used to compare the treatment groups. To determine the sample size the researchers use formulae that encounter the following factors: (a) estimate of the number of participants in the comparison group that might experience the study outcome; (b) estimate of the number of participants in the new intervention/therapy group that might

experience the study outcome; and (c) the probability of making statistical errors known as alpha and beta errors²⁴.

Alpha error (level of statistical significance) is described as the probability of concluding that the treatments differ when in reality they do not differ, and is commonly defined at 0.05. Beta error is described as the probability of concluding that the treatments do not differ when in reality they do differ, and is commonly set at 0.20. Sample size decreases as the treatment differences (alternative hypothesis) increase, whereas sample size increases as statistical errors decrease.

Intention-to-treat principle

Experimental data analysis is straightforward and usually prespecified by the study protocol; however, the application of the intention-to-treat principle should be kept in mind. This principle states that all randomized participants should be analysed in order to preserve the goals of randomization²⁵. All subjects assigned to treatment should be analysed regardless of whether they receive the treatment or complete the treatment. Approaches based on analysing patients according to the treatment they actually received may be useful for exploring some clinical questions, but should not be the primary analysis of a randomized clinical trial. In addition, a second important aspect of this analysis requires researchers to impute missing outcome data. Missing data can occur non-randomly and could be related to the therapeutic intervention used. Thus a valid intention to treat analysis should encounter data for subjects with missing measurements.

Estimating clinical effects

Clinical trials comparing devices often estimate relative treatment effects. Depending on the outcome being studied (endpoint), the reported relative effect might be a difference of means, a ratio or a qualitative difference. Estimated risk ratios and corresponding confidence intervals are important and commonly reported in randomized clinical trials. Furthermore, statistical modeling can be utilized although it is not necessary in order to investigate the possible effect of prognostic factors.

Ethical issues

Ethical considerations are intrinsic to the design and conduct of experimental studies. A number of ethical questions arise in the context of clinical trials. Is it ethical to randomize? Is it ethical to test a treatment other than the best? Can truly informed consent be received? Under what circumstances may a trial be terminated before the protocol-specified study end? Thus, experiments are often confined to treatments which would be potentially more beneficial, and ethically justifiable. No trial should be conducted without due consideration to ethical issues. These studies should be reviewed and approved by an ethics committee.

Advantages of experimental studies

- Intervention studies often provide the strongest support for a cause–effect relationship
- Possible confounding factors do not confuse the results due to the fact that treatment group allocation of the individuals is not determined by the investigator in a manner that may be considered subjective

Disadvantages of experimental studies

- A large number of research questions cannot be tested in trials
- Intervention studies may be more difficult to design than non-experimental studies due to cost and their unique ethics issues.

CONCLUSION

Well designed and thoroughly conducted observational and experimental studies provide extremely useful information that can lead clinical orthodontic practice. Table 4.5 summarizes notable differences between observational studies and clinical trials. Randomized clinical trials offer the strongest evidence of the effectiveness of treatments mainly due to the fact that treatment assignment is independent of the patient–orthodontist decision process. Although the randomized clinical trial is the optimal study design in orthodontic clinical research it may

Table 4.5 Differences between observational studies and randomized clinical trials.

Characteristic	Observational studies	Randomized clinical trials
Confounding bias	Randomization not possible Known confounders can be controlled Unknown confounders difficult to control	Randomization possible Known and unknown confounders controlled
Outcome assessment	Blinding not possible	Blinding possible
Exposure	No limit	One or two interventions
Subject selection	Broad range of patients can be included	Strict inclusion and exclusion criteria apply
Cost	Comparatively low	High

not always be feasible. An understanding of research design essentials is useful for orthodontists to interpret published research and assess the applicability of findings to everyday orthodontic practice.

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5

Determinants of Tooth Movement: Molecular Response of Periodontal Ligament and Bone to Loading

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INTRODUCTION

Orthodontic tooth movement is based on the ability of alveolar bone tissue to remodel. More than a century since the first publication by Sandstedt¹, on the experimental investigation of orthodontic tooth movement, a substantial amount of knowledge has accumulated on the sequence of events that follow force application to alveolar bone tissue. Wires and brackets exert forces on the teeth, which are delivered to the surrounding periodontal tissue and to the functional units, the cells and the extracellular matrix, that are embedded within the tissue. Cells respond by a series of actions at a molecular level that finally result in the desired or planned tooth movement and in the architectural reorganization and remodeling of the whole surrounding alveolar bone structure.

Recent developments from the area of bone biology have shed light on the biological phenomena underlying force-induced bone remodeling. New molecules and the introduction of new experimental techniques made the follow-up of the biological basis of tooth movement more difficult and less accessible for the clinical orthodontist to follow².

The importance of load application and its significance for the development, structure and maintenance of bone and cartilage tissue has long been recognized: from the ancient shamanic practices of African and Asian tribes in reshaping the form of the skull or elongating necks to the scientific publication of Wölff's law³ in early 1892.

Bone remodeling is a phenomenon that goes on continuously throughout life, and is largely dependent on hormonal control, load application and sys-

temic factors. Load application and bone integrity are very closely related and dependent. Due to zero gravity conditions and absence of loading, astronauts lose about 1% of bone mass per week in space.

The supporting structure of the body, the skeleton, is remodeled throughout life by a well coordinated system of two types of cell, the osteoclasts and the osteoblasts. Osteoclasts resorb old bone while osteoblasts lay down new bone in the resorbed areas. The whole system works in cycles, so that the whole skeleton is continuously being renewed, while the structural integrity remains unaffected⁴. The cycle of bone remodeling is tuned by the osteoblasts and consists of a series of complex cellular and molecular events linking systemic hormones to locally produced cytokines, to growth factors and to mechanical loads.

Taking advantage of this well orchestrated system, clinical orthodontists succeed in moving teeth and regulating deformed dental arches. Similarly to orthopedists, by manipulating the application of mechanical loads they aim for changes within the mechanical environment of the cells and they can predict their biological response to achieve the desired therapeutic effect.

PERIODONTAL LIGAMENT

Orthodontists operate within the system of the tooth apparatus, consisting of the tooth, the periodontal ligament (PDL) and the surrounding alveolar bone. Forces applied to the teeth, through a variety of mechanical systems in terms of brackets, wires and

elastic modules, are transferred to the PDL tissue. This highly specialized tissue anchors the teeth to the alveolar bone. It is also the key factor in all different functions of the tooth apparatus such as deglutition, mastication and proprioceptive information about mandible position. Clinical situations provide evidence that in orthodontic treatment, the PDL is the key unit for tooth movement. Ankylosed teeth that lack PDL do not have the ability to be moved. In addition, in the areas of ankylosed teeth alveolar bone fails to develop. Dental implants used as teeth replacements cannot be moved orthodontically, because they are osseointegrated and lack PDL⁵.

Furthermore, it seems that the integrity of supporting alveolar bone is directly related to the presence of PDL and its contents. After tooth extraction, the PDL is destroyed and alveolar bone is resorbed as if it had lost its function (Fig. 5.1): the balanced bone remodeling process operating under normal functional conditions shifts to resorption activity, diminishing alveolar bone⁵. The well coordinated interaction between the bone-forming cells, the osteoblasts, and the bone-resorbing cells, the osteoclasts, directs towards bone destruction activities, most likely because of the reduction in osteoblast cell population and prevalence of osteoclast cell population. It can be postulated that the PDL acts as the source of osteoblasts supporting the bone remodeling cycle involved around the socket.

The PDL consists of cells and extracellular matrix. The cells of the PDL are fibroblasts (Fig. 5.2). They are undifferentiated mesenchymal cells that, under

certain induction and signaling, have the ability to differentiate to preosteoblasts, cementoblasts, etc. It has been shown that PDL fibroblasts isolated from human PDL tissue have the attributes of osteoblast-like cells such as increased production of alkaline phosphatase, expression of osteocalcin and response to 1 α ,25 di-hydroxyvitamin D3. Moreover, under certain cell culture conditions PDL fibroblasts can form mineralized nodules in close contact with collagen fibers similar to those formed by mature osteoblasts. It has been shown that these nodules have the microstructure of rather immature bone tissue^{6,7}.

Thus, PDL fibroblasts have the potential to differentiate to preosteoblasts and play a role in the alveolar bone remodeling induced after force application in the course of orthodontic treatment. Recent studies have shown that the PDL is also a source of stem cells, suggesting the *in vivo* regeneration of cementum/PDL-like tissues. Transplantation of these cells, which can be obtained from an easily accessible tissue resource and expanded *ex vivo*, holds promise as a therapeutic approach for PDL reconstruction following damage by periodontal diseases⁸⁻¹².

The surrounding alveolar bone is a very important part of the tooth apparatus as it senses force application during mastication and during orthodontic tooth movement and reacts by complicated tissue dynamics involving bending of the alveolus, resorption and deposition, depending on the extent, direction and duration of the applied force. While the exact biological mechanisms underlying these tissue responses are not well understood it seems that they



Fig. 5.1 Complete loss of alveolar bone after tooth extraction. Note that alveolar bone remains intact only in the areas where teeth exist.

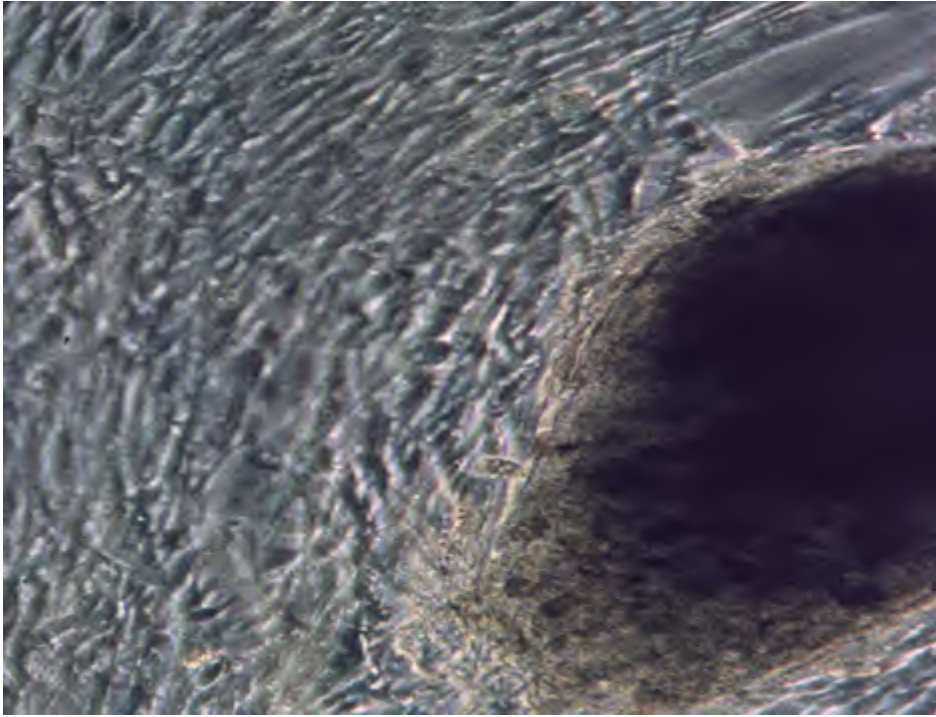


Fig. 5.2 PDL fibroblasts grown from human premolar teeth explants.

diverge from those operating in the skeleton, where loading appears to have principally a osteogenic effect^{13,14}. Despite the similarities of both alveolar bone and compact bone, the difference in their response to mechanical loading lies primarily in the existence of the PDL interface, this ‘jelly’ type of undifferentiated mesenchymal tissue acting as medium transferring information to the alveolar bone.

ORTHODONTIC TOOTH MOVEMENT

Tissue response

As external orthodontic force is applied to the teeth and moves them towards its direction, the surrounding physiological periodontal space compresses on one side and widens on the opposite side. The classic theory of compression and tension, resorption and apposition was established very early², but it was Kaare Reitan^{15,16}, early in the 1950s, who thoroughly reported on tissue reaction to orthodontic treatment in response to different types of forces (continuous versus intermittent), different force magnitudes and different types of tooth movement (tipping versus bodily movement).

Soon after the concept of differential force application was established by the classical experiments of Storey and Smith¹⁷, and the idea of optimum range of force values producing maximum rate of tooth movement came into play. It was suggested that optimal force is related to the surface area of the root. A force range of 150–250 g was sufficient to move a canine tooth rapidly, while 400–600 g of force was suggested for moving the larger molar teeth. The current concept of optimal force is based on the hypothesis that a force of a certain magnitude and temporal characteristics (continuous versus intermittent, constant versus declining, tipping versus bodily) would be capable of producing a maximum rate of tooth movement without tissue damage and with maximum patient comfort¹⁸. The optimal force for tooth movement may differ for each tooth and for each individual patient. This is one of the reasons why after more than half a century of research on orthodontic tooth movement optimal force levels are not well defined. Other difficulties relate to experimental designs and include the inability of precisely calculating the distribution of stresses and strains at the level of the PDL and the control of the type of tooth movement (tipping versus bodily)¹⁸.

While force magnitude was and still is an issue of exploration the term alveolar bone bending and

deformation appeared in the literature. Animal experiments in primates¹⁹ showed that 50–100 g of force were sufficient to produce labial or lingual displacement of a tooth from its physiological rest position, and forces over 100 g caused deformation of the alveolar bone. The direction of forces also seems to be important, as horizontal forces of 50 g and more displaced the labial and lingual plates in the same direction as the applied force and in a linear manner up to 1 kg, while axial forces of the same magnitude acting as intrusive forces caused widening of the socket. In humans, forces of less than 50 g can cause noticeable alveolar bone crest bending; an applied load of 1.5 kg causes 35 μ m bending²⁰.

Although magnitude of force appears to be a decisive factor for orthodontic tooth movement, the duration of force is another important parameter. Observations of PDL tissue under stain proved that 30 minutes after force application blood vessels appeared dilated, packed with erythrocytes, while after 2–3 hours, fragmentation of erythrocytes occurred²¹. PDL fibroblasts also exhibited necrotic changes within the first 30 minutes, appearing as dilation of the endoplasmic reticulum and mitochondrial swelling, followed after 2 hours by rupture of the cell membrane and nuclear fragmentation²². Observation for longer periods, such as 1–7 days, provides evidence that force application causes collapse of the blood vessel walls and extravasation of their contents. Cell kinetics experiments of PDL tissue under strain, showed a burst in mitotic activity after 2 hours, suggesting that after force application G₂-blocked cells enter the cell cycle and undergo mitosis, while G₁-blocked cells synthesize DNA²³.

Following orthodontic force application, different tissue responses are clinically observed in the so-called compression side, where alveolar bone is resorbed, and in the tension side, where alveolar bone is deposited. Despite the differential tissue responses in the two sides, histomorphometric experiments on PDL tissue showed similarly increase in cell proliferation measured by ³H-thymidine incorporation and in metabolic activity measured by ³H-uridine incorporation, questioning the existence of differences in cell response between the two sides²⁴.

Many bone biologists suggest that mechanical load acts as an osteogenic stimulus in the skeleton^{13,14} while in the case of orthodontic tooth move-

ment mechanical load initiates resorption activities²⁵. The difference in the interpretation of the clinical findings of orthodontic tooth movement primarily lies in the limitations of the widely accepted 'tension and compression' model. To date it is not clear whether, in loaded PDL, strain is similarly applied on the compression site as well as on the tension site. As Meikle suggests², stretching of the principal fiber bundles does not seem to generate tension and differential pressures can develop within the tissues of the periodontium.

Following developments in orthopedics, in an effort to elucidate the resorption apposition phenomena relating to orthodontic tooth movement, during the 1960s and 1970s, the piezoelectric effects and their involvement in the regulation of bone remodeling attracted much attention in orthodontics. After proving that electrical potentials are generated in dog mandible following mechanical force application to the teeth, Zengo *et al.*²⁶ proposed that electrical potentials are responsible for regulating osteogenesis and bone resorption in the course of orthodontic tooth movement. Soon after, all bone remodeling phenomena in orthodontic treatment were seen in light of this newly developed idea. The interpretation of the scientific data on orthodontic-induced bone remodeling in the view of piezoelectricity proved to be problematic because piezoelectric phenomena are also generated in dead hard bone tissue, the response of the hard alveolar bone wall, not living PDL tissue. It is well accepted today that stress-generated electrical potentials elicited during orthodontic tooth movement represent a physical phenomenon, secondary in response to alveolar bone bending. Apparently, while PDL tissue and its contents are the key regulators in the biological response to orthodontic tooth movement, electric potentials represent the alveolar tissue response to horizontal deformation and are indicative of the bone resorption and apposition sites.

Cellular response

In a scientific era where everything is seen under the light of cell–cell and cell–matrix interactions, the biological response of orthodontic tooth movement took a turn towards the understanding of the cellular mechanisms involved. Although histological studies had shed the initial light on the socket

response to orthodontic tooth movement, many biological phenomena, such as resorption and apposition on pressure and tension sites respectively, remained obscure.

Various types of experimental designs were introduced in order to study the cellular response to orthodontic tooth movement. Pavlin *et al.*²⁷ and Pavlin and Gluhak-Heinrich²⁸ developed a mouse model for studying mechanically induced regulation of osteoblast- and cementoblast-associated genes. The responses of osteoblast-associated genes to mechanical loading were 10–20-fold greater than the increase in the numbers of these cells, indicating that the induction of differentiation and an increase of cell function are the primary responses to osteogenic loading. The progression of the osteoblast phenotype in the intact mouse periodontium was several-fold faster compared with that in cultured cells, suggesting that the mechanical signal may be targeting osteoblast precursors in the state of readiness to respond to an environmental challenge, without the initial proliferative response. An early response of alkaline phosphatase and bone sialoprotein genes was detected after 24 hours of treatment, followed by a concomitant stimulation of osteocalcin and collagen I between 24 and 48 hours, and deposition of osteoid after 72 hours. Furthermore, histological observations of paradental tissues after 3 days of treatment, revealed a response favoring a fast onset of tooth movement and deposition of new osteoid. Starting with day 2, the osteoblast number showed a modest but consistent increase. Only a moderate increase in the number of osteoblasts in the areas of otherwise intense bone matrix synthesis suggests that, during bone formation, proliferation of cells has a smaller role compared to a marked increase in differentiation of individual cells.

To date, results demonstrate a defined temporal pattern of cell-specific gene regulation in periodontal osteoblasts mechanically stimulated to differentiate and deposit bone matrix. Melcher and Turnbull²⁹ developed an organ culture system for mouse molar explants and Yen and Melcher³⁰ further improved it as a modified continuous-flow culture system. While both systems had their difficulties, efforts were made to establish a reliable and controlled system. Based on the hypothesis that remodeling mechanisms are alike for all fibrous joints, Meikle *et al.*³¹ developed an organ culture system from rabbit cranial sutures. Following the assumption that a controlled system

of forces applied to sutures of the craniofacial skeleton mimic the force system generated in the PDL, a 2–3-fold increase in protein synthesis and a 2-fold increase in collagen synthesis of the sutures, could be detected after 6 hours. Studies on the collagen behavior of stressed sutures proved that while control sutures synthesized type I collagen, stressed sutures synthesized 20% more collagen type III³², suggesting that the biomechanical environment of a cell is an important regulator of collagen type synthesis. Collagen is a founding element of extracellular matrix and seems to be highly affected by stress conditions. Enzymes such as the matrix metalloproteinases (MMPs), collagenase, and stromelysin, involved in the degradation of extracellular matrix, were found to be stimulated after mechanical deformation while the expression of the tissue inhibitor of metalloproteinase (TIMP) was down-regulated^{33,34}. Most recently, these results were confirmed by *in vitro*³⁵ and *in vivo*³⁶ studies by using cDNA probes and antibodies to human, mouse and rat proteins. The significance of this reaction is not clear, but it seems likely that changes in the functional response of the extracellular matrix are prerequisites for further cell responses associated with cell differentiation and proliferation.

Molecular response

Although the cellular response of PDL tissue and its contents to orthodontic tooth movement provided some insight into the biological response and facilitated to some degree the interpretation of clinical data, it is the study of the molecular mechanisms involved in the mechanical stimulation of PDL cells which will elucidate the whole mechanotransduction signaling pathway. Eventually, understanding the signal transduction pathway will allow for therapeutic intervention in the form of small compounds mimicking orthodontic force application responses, and ultimately improving many parameters of orthodontic treatment.

Many cell culture systems were used in order to mimic orthodontic force application *in vivo*. These include culturing fibroblasts in collagen substrates, which in turn can be stretched, or employing the flexible bottom culture dish system. According to the latter, cells cultured on petri dishes with a flexible membrane bottom, can be stretched by being

placed on top of a convex template. The stretch applied can be varied and the system delivers more stretch in the center than at the periphery of the dish. Both systems provide static stretch while the later developed Flexicell system could stimulate cell cultures in an intermittent manner.

The earliest reports showed an involvement of prostaglandins, cyclic AMP (cAMP), inositol phosphates and changes in intracellular Ca^{2+} concentration via stretch-activated ion channels³⁷⁻⁴⁶.

The above-described pathways are general signaling pathways and they constitute the cell response to various extracellular stimuli; the exploration of bone-specific mechanical-load-related signaling pathways has attracted researchers' attention. Cells inside the tissues as well as in cell cultures are not 'floating around' but they are connected with the extracellular matrix or their substrate by specialized sites of cell attachment termed focal adhesions. Specialized proteins, the integrins, 'run' through the cell membrane and link actin-associated cytoskeletal proteins to the extracellular matrix⁴⁷. They are composed of structurally distinct subunits (α and β) which, in combination, form heterodimeric receptors with unique binding properties, for collagen, laminin, vitronectin, etc. Outside the cell, focal adhesions are sites where integrin receptors physically link cytoskeletal proteins, namely talin, vinculin, α -actinin and paxillin, with the extracellular matrix and adjacent cells⁴⁸. Actions causing disturbances in this link create cellular responses associated with migration, proliferation and differentiation^{49,50}. Thus, integrins function both as cell adhesion molecules and intracellular signaling receptors.

Mechanical forces applied to cells most likely cause perturbation of the cell-to-cell and cell-to-extracellular matrix attachment and act as a signals for the further biochemical response of the cell. Shyy and Chien⁵¹ postulated that the integrins constitute a mechanoreceptor and that stress fibers are necessary to transmit the applied forces. Scientific data provide evidence that changes in cell signaling in response to mechanical deformation are downstream of events mediated by integrins at focal adhesions. Meyer *et al.*⁵² found that mechanical stress altered the cAMP signaling cascade and downstream gene transcription through signals generated by activated integrin receptors, in a G-protein-dependent manner. β_1 -integrin subunit mRNA expression was increased following mechanical stimulation of bone cells⁵³.

It becomes apparent that cell attachment to extracellular matrix through focal adhesions enables cells to recognize mechanical perturbation and further transmit the signal intracellularly through the cytoskeleton, mechanosensitive ion channels, phospholipids and G-protein-coupled receptors in the cell membrane. To this extent, the low molecular weight small-GTP binding proteins of Ras-related GTPases, Rab and Rho, as well as the mitogen-activated protein kinase (MAPK) subtypes which are components of integrin-mediated signaling, have been shown to be altered in mechanically stretched PDL fibroblasts⁵⁴⁻⁵⁸. Research data provide evidence that signaling through MAPKs is essential for the early stages of osteoblast differentiation. To this end, it was shown that low level continuous mechanical strain of human PDL cells (i.e. osteoblast-like cells capable of undergoing osteoblast differentiation in response to a variety of extracellular stimuli) rapidly induces the principal constituents of the transcription factor activator protein 1 (AP-1), c-Jun and c-Fos⁵⁸⁻⁶¹. Activation of the transcription factor AP-1 via ERK/JNK signaling, enhances its DNA-binding activity on osteoblast-specific genes, hence modulating their expression rate. This results in a shift towards differentiation and marks the onset of the osteoblast phenotype. Recently, the role of the bone specific transcription factor core-binding factor A1 (CBFA1) or Runx2 was elucidated. Runx2 binds to the osteoblast-specific *cis*-acting element 2 (OSE2), which is found in the promoter regions of all the major osteoblast-specific genes (i.e. osteocalcin, type I collagen, bone sialoprotein, osteopontin, alkaline phosphatase and collagenase-3) and controls their expression. Conceivably, Runx2 expression plays a key role during osteoblast differentiation and skeletogenesis. Runx2 was also found to be a pivotal sensor of mechanical stimulation applied to PDL fibroblasts. Specifically, it was shown that low-level mechanical stretching of PDL cells directly upregulates the expression and DNA binding activity of Runx2^{60,61}. This effect is mediated by stretch-triggered induction of ERK-MAPK, as this kinase was found to physically interact and phosphorylate endogenous Runx2 *in vivo*, ultimately potentiating this transcription factor. These data provide a molecular link between mechanostressing and stimulation of osteoblast differentiation.

Summarizing the signaling pathway cascade following mechanical stress application in undifferenti-

ated mesenchymal PDL cells with the potential to differentiate to osteoblasts, it becomes apparent that (Fig. 5.3):

1. Disturbances in cell attachment through integrin involvement
2. Are transmitted to the cytoplasm via small-GTPases (Rho and Rab)
3. Activating through MAPK (ERK, JNK) cascades
4. Bone-specific (Runx2) and bone-related transcription factors (-jun, c-fos)
5. Stimulating their DNA-binding potential to specific genes linked to osteoblastic differentiation (ALP, osteocalcin, collagen type I)⁵⁴⁻⁶¹

This ultimately translates to changes in gene expression and reprogramming towards the osteoblast phenotype. Differentiated PDL cells can now produce

cytokines that induce osteoclast differentiation and initiation of bone resorption activities. The cycle of this orthodontic force-induced bone remodeling is maintained through the existence of the PDL tissue. It seems that the PDL, with its pluripotent cell population, acts as a cell source providing undifferentiated cells that, under mechanical stress stimulation as in orthodontic tooth movement, differentiate to osteoblasts. Mature osteoblasts produce cytokines, i.e. receptor activator of nuclear factor κ B ligand (RANKL, a member of the membrane-associated tumor necrosis factor (TNF) ligand family) and osteoprotegerin (OPG) which induce osteoclast differentiation and bone resorption activities.

It seems that the study of the mode of action of cytokines will provide a lot of information regarding remodeling procedures and specifically the interaction between osteoblasts and osteoclasts. Cytokines

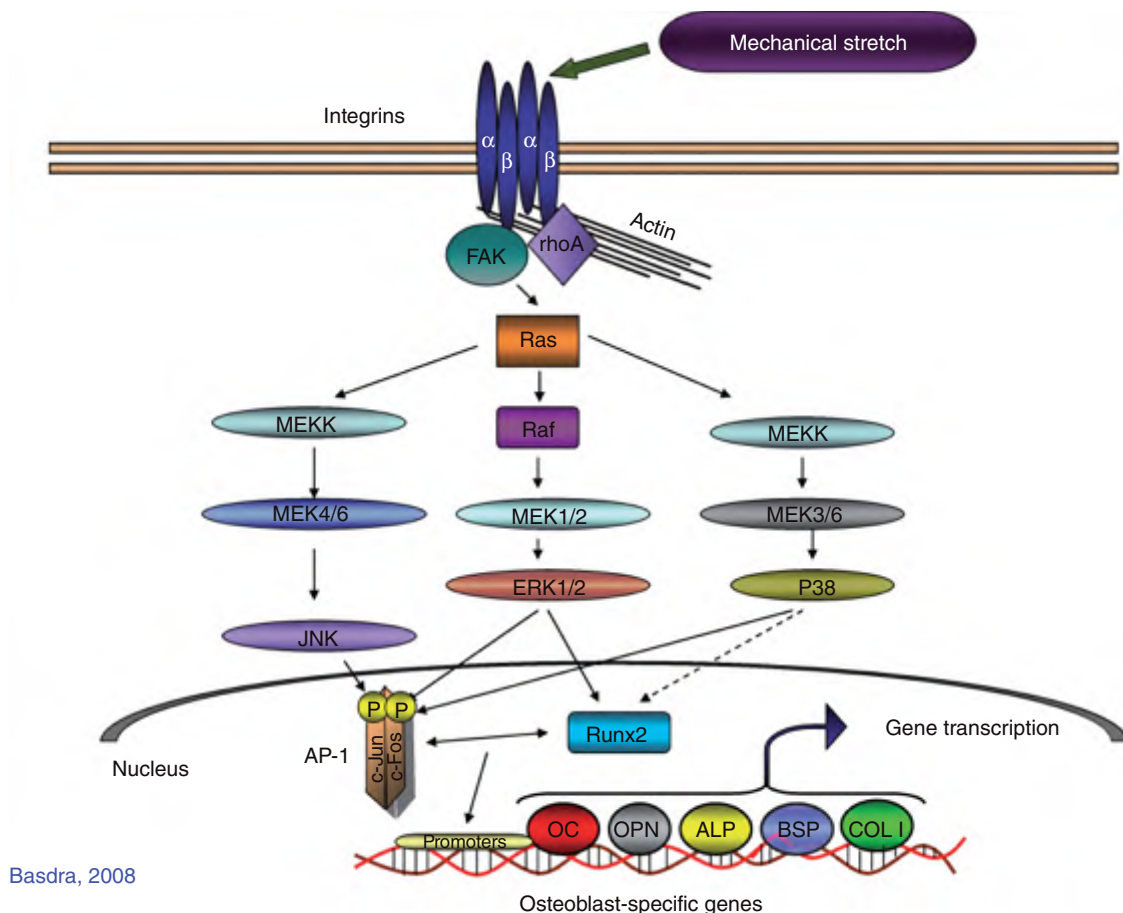


Fig. 5.3 Mechanical forces, as an external stimulus, acting on pre-osteoblastic cells such as PDL fibroblasts, activate transcription factors which in turn influence the gene expression of target genes modifying cell maturity and function.

are proteins produced by connective tissue cells such as fibroblasts and osteoblasts and are involved in physiological bone turnover and remodeling. These low molecular weight proteins (MW < 25 kDa) regulate or modify the action of other cells in an autocrine or paracrine mode. The synthesis and/or action of cytokines is controlled by systemic hormones and mechanical stimuli. One of the first recognized bone-related cytokines was interleukin-1 (IL-1)^{62,63}. TNFs also stimulate bone resorption and inhibit bone formation *in vitro*⁶⁴. A very important cytokine produced by osteoblast cells is the receptor activator of nuclear factor κ B ligand (RANKL, a member of the membrane-associated TNF ligand family). RANKL plays a pivotal role in osteoclast formation and function^{65,66}. Osteoclast precursors and osteoclasts express the receptor of RANKL, namely RANK, on which RANKL binds, inducing osteoclast differentiation (Fig. 5.4). Parameters

involved in resorption activities such as parathyroid hormone (PTH), IL-1, IL-6 and TNF- α , act by upregulating RANKL expression by osteoblast precursors and osteoblasts. Another very important cytokine also produced by osteoblast precursors and osteoblasts is OPG⁶⁷. OPG inhibits osteoclast function by competing with RANKL for the membrane receptor RANK. RANKL and OPG are produced by PDL cells⁶⁸. Culture media from compressed PDL fibroblasts stimulated osteoclastogenesis in stromal cell cultures and upregulated RANKL mRNA expression⁶⁹. It seems that the biochemical interplay and its regulation of these two cytokines will enlighten the signaling pathway of orthodontic force-induced bone remodeling, and will be a target for future pharmacological intervention in order to influence and control orthodontic treatment.

Although an old issue, inflammation as cell response to orthodontic force application recently

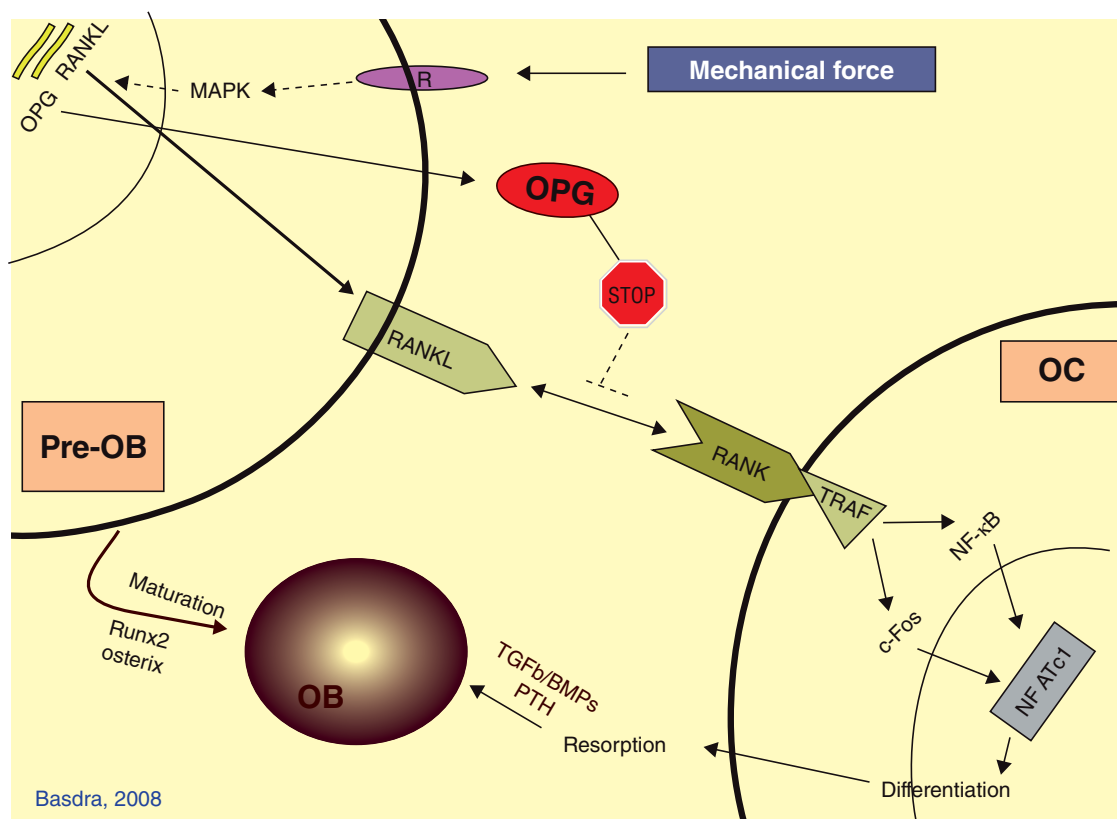


Fig. 5.4 Force-induced bone remodeling. Orthodontic force applied to the teeth is transmitted through the periodontium to the cells residing within it. The PDL pruripotent cells respond in a biological manner that elicits differentiation phenomena and establishes the osteoblastic phenotype. Cytokines produced by mature osteoblasts such as RANKL and OPG induce differentiation of the osteoclasts initiating resorption activity, finally changing the architectural structure of the surrounding alveolar bone and orthodontically moving the teeth. (Pre-OB, preosteoblasts; OC, osteoclasts)

came of age. Scientific data have shown that mechanical loading causes inflammatory responses inside the cells similar to those caused by inflammatory agents⁷⁰. More specifically, in loaded bone cells, nuclear factor kappa B (NF- κ B) is involved⁷¹. NF- κ B is a nuclear transcription factor found in all cell types and is involved in cellular responses to stimuli such as stress, cytokines, free radicals, ultraviolet irradiation and bacterial or viral antigens. NF- κ B plays a key role in regulating the immune response to infection. Moreover, NF- κ B is a transcription factor known to play a key role in the regulation of genes which are involved in growth and developmental processes. Consistent with this role, incorrect regulation of NF- κ B has been linked to cancer, inflammatory and autoimmune diseases, septic shock, viral infection and improper immune development. Today some scientists even suggest inhibition of the action of the NF- κ B in order to treat inflammation and cancer⁷². Inflammation today is considered a well preserved response mechanism to various extracellular signals. It seems that mechanical signals also create a stress stimulus, to which cells respond in a way manifested through inflammation-related processes. Orthodontic tooth movement should not be considered as an inflammatory process but as a response to mechanical stimuli by signaling pathways well preserved during evolution.

Despite extensive investigation during the last two decades into tissue and cell response to orthodontic tooth movement, our knowledge remains rather limited. Although some of the components involved in the mechanical stress signaling pathway have been identified, our understanding of optimal orthodontic force is far from complete. To date no data exist at a cellular and molecular level on the mode of action of different orthodontic treatment modalities. The different orthodontic techniques that are used in orthodontics, i.e. light wire, bioprogressive, have been studied only from the biomechanical point of view. Moreover, wires with different material properties or frictionless brackets are being used without any scientific support at cell reaction level. The future in orthodontics calls for: (a) elucidation of the molecular mechanisms that are involved in the PDL cell response; (b) manipulation of the components involved in the response through pharmaceutical intervention; and (c) exact characterization of optimal orthodontic forces, treatment mechanics

and treatment means, in order to plan the optimal orthodontic treatment for each individual.

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6

Efficiency and Treatment Outcome with Self-Ligating Brackets

Nikolaos Pandis, Peter G. Miles and Theodore Eliades

INTRODUCTION

The introduction of the self-ligating bracket concept in orthodontics can be traced back several decades; Harradine reports that the concept of self-ligation is as old as that of the edgewise bracket itself and was described first by Stolzenberg in 1935¹. Although numerous designs were introduced in the following decades, self-ligation did not become popular until the introduction of the SPEED appliance (Strite Industries Ltd, Cambridge, Ontario, Canada) by Hansen in the early 1980s². In the 1990s, other companies introduced self-ligating appliances and, today, almost all major orthodontic companies offer some form of self-ligating appliance of either the passive or the active form. The popularity of the Damon (Ormco, Glendora, CA) and the In-Ovation R (GAC, Bohemia, NY) brackets has forced other companies to follow suit and introduce similar systems in an effort to be up to date with the current trends. Orthodontic companies have strong incentives to introduce new innovative appliances which are superior to mainstream products in order to differentiate themselves in the competitive market place. However, the question that arises is: do self-ligating brackets outperform conventional brackets, and deliver what they promise?

In this chapter we will deal with aspects of the treatment efficiency of the self-ligating appliances as they compare with the conventional systems by presenting and evaluating the available scientific evidence in the peer-reviewed orthodontic literature. It is noteworthy that the data available on self-ligation is limited and there is no published research information for several bracket systems.

The obvious advantages of self-ligating brackets involve the elimination of certain utilities or materi-

als such as elastomeric modules along with the process or tools associated with their application, although some then require specific tools to help engage or disengage the archwire from the clip or gate mechanism. This brings a number of favorable features in treatment including the elimination of potential cross-contamination with elastic ties and consistent engagement without the undesirable force relaxation of elastomeric modules. Numerous claims have been made regarding: the reduced risk for enamel decalcification arising from the elimination of the retentive site for plaque accumulation; reduced friction in sliding mechanics; and assumed low magnitude forces resulting in reduced side effects³⁻¹¹. Moreover, through the past decade the initial clinical handling difficulties associated with use of self-ligating brackets have been overcome and the application of these appliances has been significantly simplified.

Most of the advantages of self-ligation remain largely presumptuous. For example, enamel decalcification risk has not been shown to vary relative to conventional edgewise brackets; friction variants have not been explored systematically in clinical setups¹²; and root resorption has not been found to vary between self-ligating and conventional brackets¹³. Whereas there is a significant body of evidence suggesting that ligation with elastomeric modules and especially with stainless steel ligatures increases friction, the effect of this variable remains unknown *in vivo*. Specifically, a clinical trial has demonstrated that the use of archwires with different surface roughness and friction, *in vitro*, was not accompanied by different tooth movement rate clinically¹⁴. This effect probably resides on various clinical variables which cannot be simulated in currently available laboratory configurations including that the

rate of sliding movement has been typically chosen arbitrarily, resulting in a non-standardized parameter that makes comparison of the results from different studies impossible. Nonetheless, when a standard rate is chosen, fundamental discrepancies between the clinical situation and the research environment arise. Therefore the use of movement rates described by simple first-order kinetics is inappropriate¹². Also, a dependence of friction on the velocity at which the surfaces slide past each other has been shown, an effect which has not been considered in related research¹⁵. Finally, observations of the structure and morphology of retrieved nickel–titanium archwires provided proof of the presence of calcified protein integuments, which constitute a variable not incorporated into *in vitro* studies¹⁶.

A discussion will follow based on the available scientific evidence analyzed into the variables related to the orthodontic treatment. Due to the limited number of publications on treatment outcome and efficiency with self-ligating brackets, all peer-reviewed studies will be individually presented.

TREATMENT DURATION

One of the first studies published on the treatment efficiency of self-ligating brackets was by Eberting *et al.*¹⁷ This retrospective clinical study compared the effectiveness and clinical efficiency of the first-generation Damon SL self-ligating brackets to those of conventional brackets ligated with either stainless steel or elastomeric ligatures. Treatment duration, number of visits and quality of treatment outcomes, using the American Board of Orthodontic (ABO) model and panoramic radiograph grading criteria, were recorded. Additionally, responses obtained through a mailed questionnaire of the 215 patients included in the study addressing how their orthodontic treatment progressed and finished were evaluated. The authors found that the cases bonded with the Damon SL finished significantly faster and required fewer visits to complete their treatment. This was a three-center study with two experienced orthodontists in the two practices and the residents of Temple University performing the treatment at the third center. The resultant ABO scores varied among practices with the University residents achiev-

ing lower-quality outcomes with the Damon SL system compared to the other practices.

Orthodontic treatment efficiency with studies that do not satisfy the criteria of a prospective randomized trial, conducted *post mortem* based on treatment records of more than one practitioner, or questionnaires of patients, and even comparative trials that include a large variety of malocclusions treated with a wide array of methods and modalities, thus precluding a means to isolate confounding variables, may be problematic. This is because the use of various treatment auxiliaries and utilities such as intermaxillary elastics, differing archwires and mechanics and incorporation of treatment variability in the form of extractions or extraoral appliance, introduces a variable, which if not carefully weighted in both populations, may distort the results^{17,18}. Retrospective studies include the possibility of outcome bias, since the treatment results are known prior to assignment of bracket type to patient group. Also, data collection relies on the accuracy of treatment records, whilst studies employing more than one practice to collect larger numbers of patients, present the additional complicating factors of interoperative variability in materials handling and clinical management.

Harradine¹⁸ in age-, type-, extraction pattern-, and severity of malocclusion-matched cases, evaluated treatment duration, outcome quality as measured by PAR scores, and handling efficiency during archwire changes. The author found a significantly reduced treatment time with the Damon SL bracket, comparable PAR scores, and insignificant time savings in archwire changes compared with the conventional brackets. The reduced treatment times reported by Eberting (25 months) using the Damon SL bracket were still greater than the initial conventional appliance treatment duration (23.5 months) reported by Harradine. This fact implies that the reduction in treatment duration may be due to a change to more efficient treatment systems and not the choice of bracket. Alternatively, average cases may not respond any differently to SL brackets, but more severely crowded cases and extraction cases may; these notions have been questioned^{19,20}. Finally, there may be no time savings and reported differences may be due to other factors such as altered mechanics or unintentional bias.

Miles *et al.*²¹ conducted two different studies with similar protocols where they compared treatment

variables between conventional and self-ligating brackets. In the first study they compared the Damon2 self-ligating with Victory (3M Unitek, Monrovia, CA) edgewise brackets. Sixty consecutive patients participated in a split-mouth design. One side of the lower arch was bonded with the Damon2 bracket and the other with a standard twin bracket, alternated with each consecutive patient. The irregularity index was measured for each half of the arch at baseline, at 10 weeks for the first archwire change, and at another 10 weeks at the second archwire change. At the first archwire change at 10 weeks ($p = 0.001$) and the second archwire change at 20 weeks ($p = 0.001$), the standard bracket had achieved a lower irregularity index than the Damon2 bracket. The standard bracket was statistically more efficient than the Damon2 bracket during alignment although, clinically, the difference was minimal. However, one may argue that by using a split-mouth design where conventional and self-ligating brackets are mixed may negatively affect the sliding/friction characteristics of the self-ligating brackets. This is similar to the Damon wire sequences as the archwires use a crimpable stop, which also prevents sliding past this point either side of the archwire. Additional findings were that patients preferred the look of the standard bracket over the Damon2 ($p < 0.0005$) and that Damon2 brackets had a higher bond failure rate during the study ($p < 0.0005$).

To avoid this concern with a split-mouth design, the second study²² conducted by Miles *et al.* used a similar measurement protocol but alternated subjects between the SmartClip (3M Unitek, Monrovia, CA) self-ligating bracket and the Victory edgewise bracket. Fifty-eight patients participated in this prospective trial. The results indicated no difference in irregularity at the start of treatment. At 10 weeks, subjects treated with conventional brackets had a lower irregularity index than subjects treated with SmartClip brackets (mean difference: 0.7 mm; $p = 0.005$). After 20 weeks there were no statistically significant differences in irregularity between the two groups (mean difference: 0 mm; $p = 0.82$). The SmartClip self-ligating bracket was no more effective at reducing irregularity during the initial stage of treatment than a conventional twin bracket ligated with elastomeric modules or stainless steel ligatures (Table 6.1). The above studies followed the prospective clinical trial protocol and minimized confound-

Table 6.1 Comparison of alignment efficiency for SmartClip and conventional twin brackets. Data from Miles²¹ with permission from The Australian Orthodontic Journal.

Group		Irregularity index (mm)	p
Initial	SmartClip	5.7	0.86
	Conventional	5.8	
10 weeks	SmartClip	2.3	0.005
	Conventional	1.6	
20 weeks	SmartClip	1.4	0.82
	Conventional	1.4	

ing factors by focusing on a particular segment of the treatment.

Pandis *et al.*¹⁹, in a prospective study of 54 patients, evaluated mandibular incisor alignment efficiency and dental arch changes using models and cephalometric radiographs. Mandibular crowding was selected as a model for examining the efficiency of brackets because correction of this discrepancy largely depends on the ‘free play’ or clearance of the archwire inside the slot walls. Although canine retraction with sliding mechanics is the basic scenario where free play is the dominant mechanotherapy, this model carries some fundamental difficulties pertinent to adjusting the rate of movement, estimating the pre- and post-movement condition and assessing the relative efficiency of appliances. On the contrary, alleviation of crowding is a treatment process where both initial and terminal stages can be quantitatively determined with the use of irregularity index, and measurements can be performed regardless of teeth inclination or rotations as in retracting canines.

Although the Damon system was faster in reaching alignment and in some cases in a statistically significant manner, the overall advantage was of small clinical importance. The results of this study suggest that Damon2 brackets are not more efficient in terms of treatment time (Damon2 104 days, conventional 125 days) required to resolve severe anterior mandibular crowding relative to conventional appliances. Moderate crowding alleviation was faster with Damon2 brackets (81 days) compared to conventional appliances (104 days) and reached statistical significance (Figs. 6.1, 6.2). This difference may be assigned to the substantially higher ‘free play’ of the self-ligating appliances, an effect which facilitates an undisturbed labial movement of the

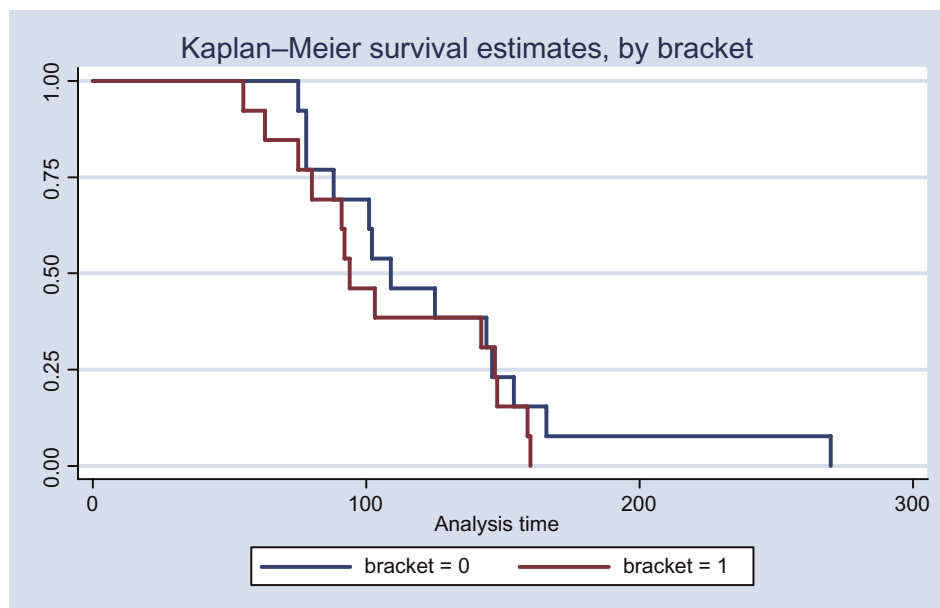


Fig. 6.1 Graph depicting the variation of treatment duration by bracket for high crowding cases ($IR > 5$), data from Pandis *et al.*¹⁹ The y axis provides the proportion of cases still in treatment (not aligned) at different time variants (days on x axis). By drawing a line perpendicular to the x axis at a given time value, the proportion of cases not completed for each bracket group (conventional or self-ligating) is extrapolated. Note the pattern of the individual graphs throughout the entire treatment period indicating no difference in time to completion at a given treatment time. (bracket 0, conventional; bracket 1, self-ligating)

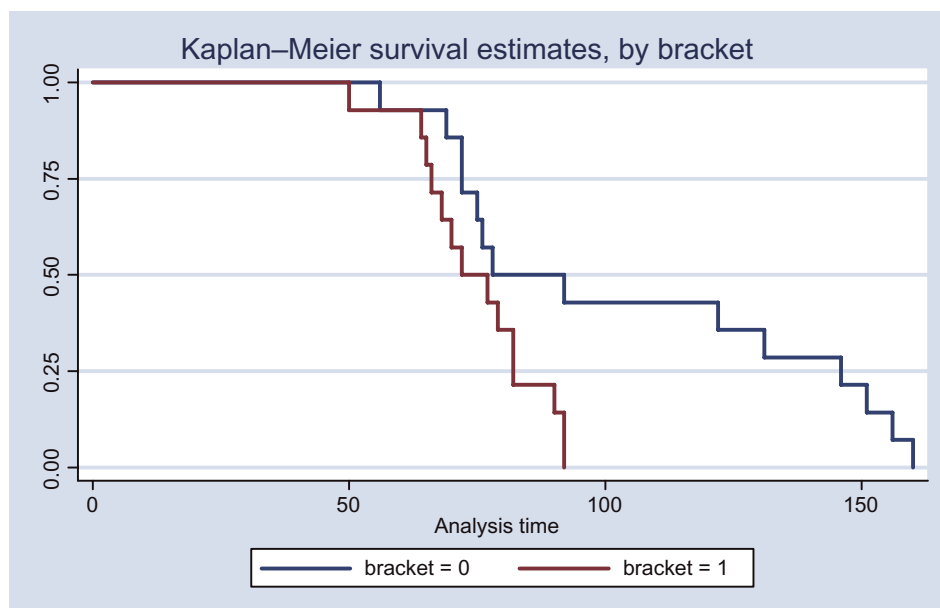


Fig. 6.2 Graph depicting the variation of treatment duration by bracket for low crowding cases ($IR < 5$), data Pandis *et al.*¹⁹ The y axis provides the proportion of cases still in treatment (not aligned) at different time variants (days on x axis). By drawing a line perpendicular to the x axis at a given time value, the proportion of cases not completed for each bracket group (conventional or self-ligating) is extrapolated. Note the pattern of the individual graphs throughout the entire treatment period indicating a difference in time to completion at a given treatment time. (bracket 0, conventional; bracket 1, self-ligating)

crown. In contrast, elastomeric modules or steel ligatures act as obstacles because of the stress they exert on the wire adjacent to the bracket sides, precluding the free sliding of wire into the slot walls, thus adversely affecting the movement rate. This advantage of self-ligation over conventional ligation is eliminated when crowding exceeds a certain extent and the availability of space within the arch is restricted. In the latter case, the relative efficiency of the bracket system seems to be of limited use because of difficulties that are beyond the capabilities of mechanotherapeutical configurations. Interestingly, Henao and Kusy in an *in vitro* study²³, where active and passive self-ligating brackets were evaluated, concluded that when clearance was substantial, the self-ligating brackets with slides performed better than those with clips. However, as malocclusion became more severe and archwire size reduced overall clearance, the two self-ligating designs of slides (passive) and clips (active) performed in a similar manner. Although extrapolation from the laboratory experiments to the clinical setting should be done with caution, due to unknown variables, it appears that Henao and Kusy's findings are in agreement with the findings of the study by Pandis *et al.* discussed above.

Another explanation for achieving faster alignment on the moderately crowded cases may be the fact that in those cases it was possible to insert the 0.014" × 0.025" copper-nickel-titanium wire in the self-ligating brackets earlier in treatment. The Damon bracket resembles a tube with unyielding walls, unlike the conventional bracket that is affected by the elastic 'O' ring relaxation; when interacting with the Damon bracket the flexible rectangular wire was able to align the lower dentition in almost all cases within 1 month after its insertion. Another possible explanation is that the wires used were of different thicknesses in the first order. The second archwires used were a 0.014" × 0.025" Damon copper-nickel-titanium for the Damon2 bracket group whereas the conventional bracket group went to a 0.020" round medium Sentalloy wire. This significant difference in thickness and cross-section of the second wires in the first order could have a significant impact on control of rotation. The wires used were also from different manufacturers with differing properties. A study by Berger and Waram²⁴ demonstrates that the 0.014" Damon copper-nickel-titanium wires apply higher force

levels than other nickel-titanium wires of similar dimensions.

Additionally, the foregoing study revealed a positive effect of the severity of crowding on the treatment duration, which accounted for about 20% additional treatment time for each additional irregularity index unit added (hazard ratio for one unit irregularity index increase: 0.81, $p < 0.05$). Regarding the speed of tooth movement, low or no friction is one factor, whilst the behavior of the periodontal tissues and their limiting effect on the free movement of the teeth is another part of the equation. As the saying goes, 'it may sound impressive to say that we are driving a Ferrari but there is no warranty that we will get from point A to point B faster than with a Beetle if we are driving on a narrow, curvy and bumpy road'. Furthermore, retrieved nickel-titanium archwires provided proof of the presence of calcified protein integuments which constitute a variable not incorporated into *in vitro* studies and possibly affect free sliding and friction¹⁷. Clinicians using self-ligating brackets, especially at the mandibular incisor area are often faced with calculus deposits, inside and around the bracket slot and inside the self-ligating mechanism, finding it difficult to open and close the bracket slides or clips.

In a later study, Scott *et al.*²⁰ compared efficiency of tooth alignment and clinical effectiveness of the Damon3 and a conventional bracket system using identical wire sequences. This randomized clinical trial was conducted in two orthodontic clinics and included 62 patients with lower incisor irregularity between 5 and 12 mm, and extractions of lower first premolars. Fully ligated 0.014" nickel-titanium archwires were used as the initial archwire in both groups, followed by a sequence of 0.014" × 0.025" and 0.018" × 0.025" nickel-titanium and 0.019" × 0.025" stainless steel. Study casts were taken at the start of treatment (T1), first archwire change (T2) and at placement of the final 0.019" × 0.025" archwire (T3). There was no difference in the initial or overall rate of mandibular incisor alignment between Synthesis conventional-ligated and Damon3 self-ligated bracket systems. The Damon3 cases took an average of 253 days and the conventional cases 243 days in order to reach the stage at which the final 0.019" × 0.025" stainless steel wire was inserted. The only significant influence upon initial rate of incisor alignment was the amount of initial irregu-

larity; age, gender and bracket type were not significant predictors.

In an article, in press, Fleming *et al.*²⁵ compared the efficiency of mandibular arch alignment in three dimensions with the SmartClip self-ligating bracket system and a conventional Victory twin in non-extraction cases. This prospective randomized clinical trial involved 66 consecutive patients with a 0.016" round martensitic active nickel–titanium aligning archwire. Lower arch irregularity in three dimensions was measured pretreatment and at 8 weeks after the placement of the appliance systems. The authors concluded that overall bracket type had little influence on alignment efficiency, and it was highly correlated to pretreatment irregularity. Increasing age appeared to have a negative effect on alleviation of irregularity although this did not reach statistical significance ($p = 0.053$).

In conclusion, it appears from the available peer-reviewed studies that there is no concrete evidence

to support the notion that self-ligating brackets effectively shorten treatment duration, whilst in some cases where statistical significance was reached the difference was clinically unimportant. However, the number of publications is currently limited, and for some bracket systems there are no data available in the literature, indicating the need for further comparative evaluation of the various bracket systems. See Table 6.2.

DENTAL ARCH CHANGES

The pendulum of extraction vs non-extraction, and expansion vs non-expansion has swung both ways since the early days of the orthodontic specialty with strong believers in all treatment modality camps, whilst retention, a very important issue in orthodontics, is one of the least predictable areas of our profession. Over the years, a few simple rules of thumb

Table 6.2 Peer-reviewed publications on treatment efficiency and self-ligating brackets.

	Authors	Study type	Findings
Treatment duration	Eberting <i>et al.</i> 2001 ¹⁷	Retrospective	Decreased treatment time for self-ligating brackets
	Harradine 2001 ¹⁸	Prospective	Decreased treatment time for self-ligating brackets
	Miles <i>et al.</i> 2005 ²² , 2006 ²¹	Prospective	No difference in treatment time
	Pandis <i>et al.</i> 2007 ¹⁹	Prospective	Decreased treatment time for self-ligating brackets in some cases
	Scott <i>et al.</i> (in press) ²⁰	Prospective	No difference in treatment time
	Fleming <i>et al.</i> (in press) ²⁵	Prospective	No difference in treatment time
Dental arch changes	Pandis <i>et al.</i> 2007 ¹⁹	Prospective	Increased posterior expansion for self-ligating system
	Franchi <i>et al.</i> 2006 ²⁸	Prospective	Increased posterior expansion for self-ligating system
	Scott <i>et al.</i> (in press) ²⁰	Prospective	Increased posterior expansion for self-ligating system
Torque delivery	Pandis <i>et al.</i> 2007 ¹⁹	Prospective	No difference in torque of maxillary incisors
	Morina <i>et al.</i> (in press) ⁴⁰	<i>In vitro</i>	Significant lower torquing ability for self-ligating brackets
	Badawi <i>et al.</i> 2008 ⁴¹	<i>In vitro</i>	Significant lower torquing ability for passive self-ligating brackets
Space closure	Deguchi <i>et al.</i> 2007 ⁴⁸	Prospective	Faster canine retraction using a passive clip insert method
	Miles 2007 ⁴⁶	Prospective	No difference in retraction speed
Handling efficiency	Shivapuja and Berger 1994 ⁵⁰	Prospective	Significant time savings with self-ligating brackets
	Berger and Byloff 2000 ¹⁰	Mail survey	Significant time savings with self-ligating brackets
	Eberting <i>et al.</i> 2001 ¹⁷	Retrospective	Fewer visits for self-ligating bracket
	Harradine 2001 ¹⁸	Prospective	Insignificant time savings with self-ligating brackets
	Turnbull and Birnie 2007 ⁵¹	Prospective	Significant time savings with self-ligating brackets
Level of discomfort	Miles <i>et al.</i> 2006 ²¹	Prospective	More discomfort for self-ligating brackets with heavier wires
	Scott <i>et al.</i> 2008	Prospective	No difference for 0.014 CuNiTi wires
	Fleming <i>et al.</i> (in press)	Prospective	No difference for 0.016 NiTi wires
	Pringle <i>et al.</i> (in press)	Prospective	Pain intensity lower for the self-ligating group

appear to have received universal approval. The rules are related to the intercanine distance and the position of the lower incisor. Among the claims of self-ligation advocates is the supposedly different mechanism of action of these bracket systems. Development of the dental arches and posterior expansion distal to the canine which make non-extraction treatment more feasible have been proposed, and orthodontists are invited to think out of the box and explore uncharted territories using brackets that supposedly work differently. Although, as Thomas Kuhn²⁶ described in the 1960s, scientific revolutions do not follow a straight line and do not always build on previous knowledge, it is important to draw conclusions using randomized clinical trials instead of selected case reports when new treatment modalities are introduced in order to comparatively assess whether the new claims or theories are valid.

In contrast to various anecdotal evidence, Pandis *et al.*¹⁹ found that conventional and self-ligating brackets alleviate crowding by similar mechanisms which involve lower incisor proclination and slight expansion of the dental arches (Figs. 6.3, 6.4). The use of preformed nickel–titanium archwires precludes the absolute control of the operator over the dimensions of the dental arch. Although the overall expansion of the mandibular arch of the population treated in that trial was found to be relatively small, the intermolar width gained in the Damon2 bracket

group reached 1.5 mm above the value observed for conventional appliances. It should be noted that the wires used were not of the same shape for the two bracket systems. The Damon 0.014" × 0.025" copper–nickel–titanium wire has a broader arch-form compared to the 0.020" Sentalloy archwire used with the conventional brackets. The difference in posterior expansion may be solely attributed to the differences in the archwire forms and cross-sectional thicknesses. Additionally, expansion with preformed arches in the order of 0.5–1 mm may be negligible and could be a spontaneous effect of treatment. Traditional assumptions on the intentional ‘development of the arch’, which are translated to substantially expanding the buccal segments, have been found to be highly unpredictable, probably depending on the axial inclination of posterior teeth.²⁷

A study by Franchi *et al.*²⁸, using low-friction ligatures rather than self-ligating brackets, found a 1.7 mm increase in intermolar width when compared with conventional module ligation. This study also demonstrated that the molars tipped buccally 4°. This supports the possibility that molar expansion observed with self-ligating brackets is related to rolling or tipping of the molars rather than bodily movement or basal maxillary expansion.

Scott *et al.*²⁰, in the same study described earlier, using study models at various stages of the treat-

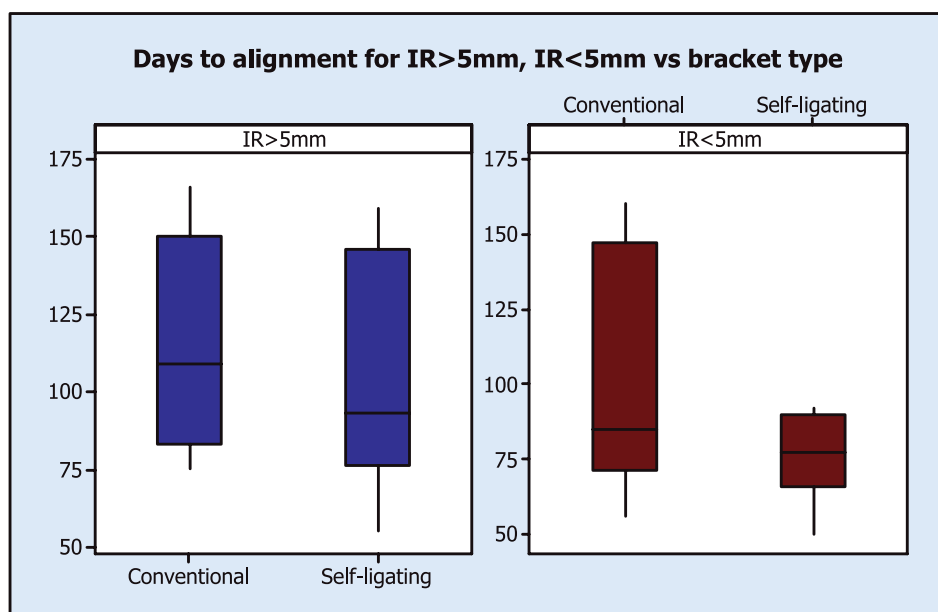
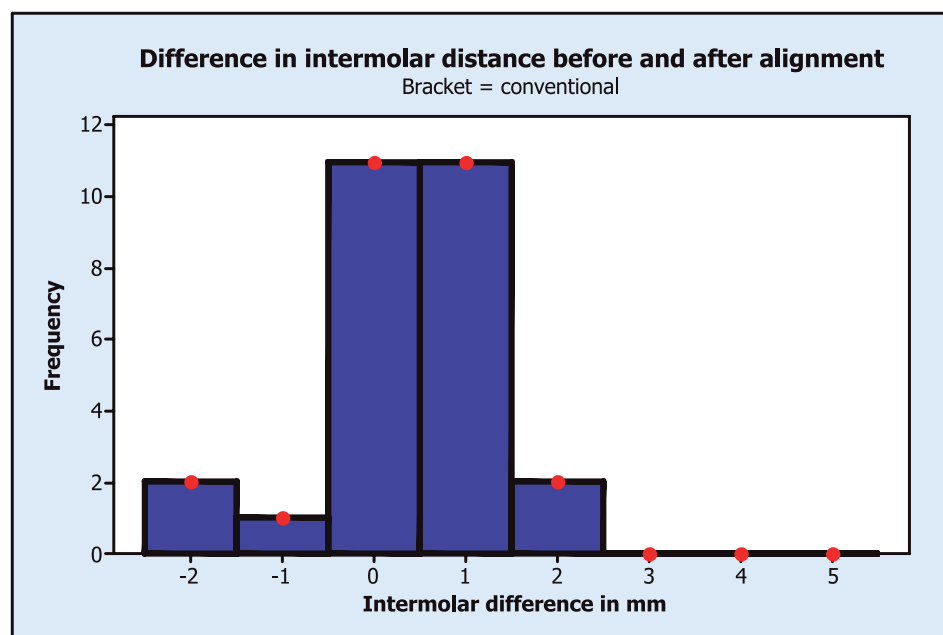
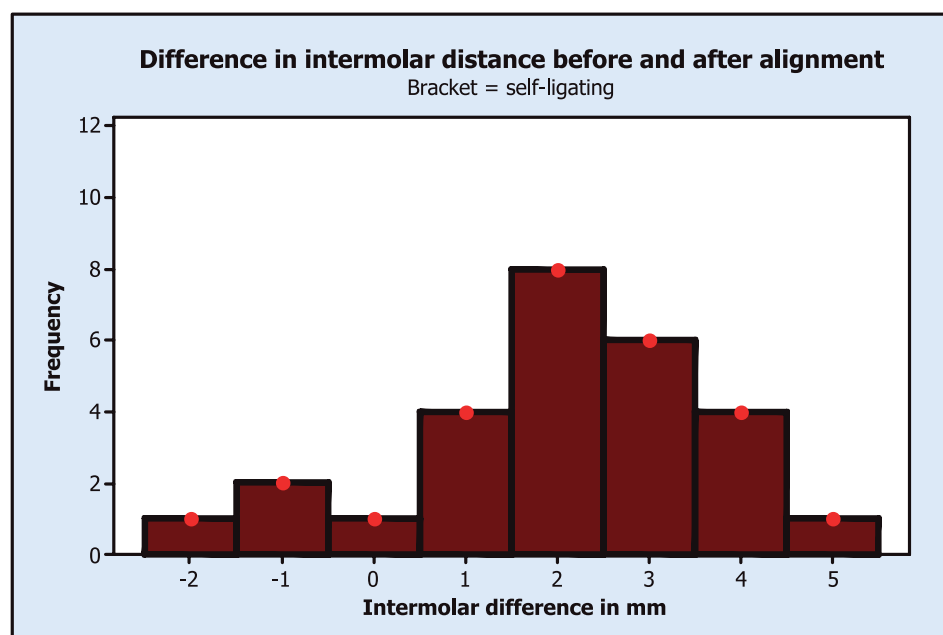


Fig. 6.3 Box plots of days to alignment between conventional and self-ligating brackets at high (IR > 5) and low (IR < 5) mandibular anterior dentition crowding cases, after Pandis *et al.*¹⁹



a



b

Fig. 6.4 Histograms of intermolar expansion between conventional (a) and self-ligating (b) brackets after mandibular anterior alignment, after Pandis *et al.*¹⁹

ment, found that alignment was associated with an increase in intercanine width, reduction in arch length and proclination of mandibular incisors for both appliances, but the differences were not significant. This particular study included extraction cases, which may explain the associated arch length reductions and distal movement of canines into the wider section of the mandible.

Fleming *et al.*²⁵ compared the effects of the two pre-adjusted appliances on angular changes of the mandibular incisors and transverse mandibular arch changes over a minimum period of 30 weeks. This prospective randomized controlled clinical trial involved 66 consecutive patients being assigned to either SmartClip self-ligating brackets or conventional pre-adjusted Victory edgewise brackets. Sub-

jects allocated to either group underwent treatment with the following archwire sequence: 0.016" round; 0.017" × 0.025" rectangular; 0.019" × 0.025" rectangular martensitic active nickel–titanium archwires and 0.019" × 0.025" stainless steel archwires. Final records were collected after a minimum of 30 weeks, with 60 patients completing the study. The authors found that bracket type had little effect on incisor inclination or intercanine, inter-first premolar, and inter-second premolar dimensions. However, the self-ligating appliance produced slightly more expansion in the molar region although this was only small (0.9 mm). Such small changes in molar expansion of 1–2 mm will only result in an additional 0.27–0.58 mm in arch perimeter which is also clinically insignificant²⁹. Proclination was less likely to arise where the labial segment was proclined at the outset and expansion was unlikely to arise during leveling and alignment in wider arches. Increased alleviation of crowding during the study period resulted in more incisor proclination and advancement.

In conclusion, it appears from the limited peer-reviewed studies that there is no evidence to support the claim that self-ligating brackets align the dentition differently compared to the conventional appliances. To reiterate, publications regarding self-ligating brackets are limited, and for some bracket systems there is nothing available in the literature, indicating the need for further comparative evaluation of the various bracket systems.

TORQUE DELIVERY

Another area of interest pertaining to the quality of the outcome of orthodontically treated cases, is the delivery of torque and the finishing position of the maxillary anterior dentition. Proper bucco-lingual inclination of both posterior and anterior teeth is considered essential to providing stability and proper occlusal relationship in orthodontic treatment. Torque of the maxillary incisors is particularly critical in establishing an esthetic smile line, proper anterior guidance and a solid Class I relationship, because undertorqued anterior teeth can preclude the distal movement of the anterior maxillary dentition. Inadequately inclined incisors deprive the dental arch of space; it has been shown that for every 5° of anterior inclination, about 1 mm of arch length is gener-

ated³⁰. On the other hand, undertorqued posterior segments have a constricting effect on the maxillary arch because they do not allow appropriate cusp-to-fossa relationships between the maxillary and mandibular teeth. Despite the abundance of empirical and research data on the necessity of adequate torque, there is a striking variability among various prescriptions with respect to anterior dentition torque values. Thus, the maxillary central incisor torque in pre-adjusted appliances ranges from 12° in the Roth prescription to 22° in the bioprogressive prescription, a variation reaching almost 100% of the suggested value³¹. Such a substantial lack of uniformity in torque values can partially be explained on the basis of individual preferences in tooth position or differences pertinent to treatment philosophy. Also, this excessively high variation might imply the inappropriateness of transferring the incisor inclination observed in esthetically pleasing and functionally sound dentitions directly to the bracket slot.

Torque delivery and control are related to several factors such as wire size and composition, material properties, variability of reported and actual wire and slot sizes, completeness of ligation, force diminution and friction. Moreover, slot and wire edges, which have been rounded, deviating from the rectangular shape or specified dimensions (larger for slots and smaller for wires) and contribute to increase play, thereby reducing the torque expression capacity of the biomechanical configuration used³². Despite the presentation of much empirical and anecdotal evidence, no documented evidence exists on the manufacturers' claims on the efficiency of self-ligating brackets in both space closure and torque control. This is particularly intriguing because of the contradictory demands involved in the mechanotherapeutical set-up for these cases as space closure with sliding mechanics requires low friction, whereas torque control necessitates the development of frictional forces between the wire and the bracket slot walls.

Filling the bracket slot by incrementally increasing the wire cross-section has been the basic mechanotherapeutic sequence of therapeutic protocols. Alternative treatment schemes such as the variable modulus orthodontics³³, advocate filling the slot in the initial stages of treatment with a low modulus wire alloy and progressively increasing the stiffness of the wire instead of its size. However, in clinical

conditions, the cross-section of the terminal archwire almost never reaches the actual size of the slot because of the associated patient discomfort and difficulty in inserting very large rectangular wires in the slot. Inevitably, a fraction of the torque that is built in the bracket remains unexpressed, giving rise to slot–wire ‘play’ or third-order clearance³⁴. The effect of this clearance factor, which was brought up early in appliance evolution³⁵, was theoretically estimated to range as high as 10°. However, the results of the theoretical torque loss do not represent the actual ‘play’ between the slot and the wire^{36–38}.

The apparent discrepancy between the estimated and measured torque loss arises from the manufacturing processes of brackets and wires. Bracket slot manufacturing introduces inclusion of metallic particles and formation of grooves and striations which may preclude the full engagement of the wire in the slot walls³⁹. Although it has been shown that reported torque differs from the actual one by 5–10%, which represents roughly 1–1.5°, the net effective torque may be lower than expected. Various bracket manufacturing processes involving injection molding, casting or milling may also affect the accuracy of the prescribed torque values. Molding exposes the material to expansion and shrinkage, whereas milling may incorporate a rough grained surface. A recent study demonstrated a high variability in the shape of the slot which deviated from the rectangular cross-section as well as in the torque reported and the actual one built into the appliance³².

Currently, the evidence available on the relative torque-transmitting efficiency of self-ligating brackets derives from a laboratory study, which showed a large torque loss for the passive self-ligating brackets, and a lower loss for the active version⁴⁰. The second study concluded that active self-ligating brackets are more efficient in torque delivery compared to passive self-ligating brackets. It is interesting to note that in order to achieve the minimum and clinically meaningful torque delivery, 15° of wire torsion for the active and 22.5° for the passive self-ligating brackets were required. This is an important finding if one considers that the aforementioned torque values exceed most if not all of the available bracket torque prescriptions⁴¹. Pandis *et al.*⁴² evaluated *in vivo* the final maxillary incisor position on extraction and non-extraction cases fitted with conventional and Damon2 brackets. The authors concluded that self-ligating brackets seem to be equally

efficient in delivering torque to maxillary incisors relative to conventional brackets in extraction and non-extraction cases. The contradicting evidence may be explained on the basis of the clinical application of materials and the factors intervening in clinically handling the torque stages. Treatment of patients involves application of reverse curve archwires, a factor which was not considered in the laboratory set-up. Also, the clinician has the option of adding torque to the wire, a factor which cannot be standardized in *ex vivo* experimental configurations. In fully bonded dentitions the forces and moments applied to teeth may be different compared to the simplified form of laboratory set-ups because of the simultaneous presence of second-order bends⁴³.

Cases receiving a 0.019 × 0.025" stainless steel archwire as the final wire in the 0.022" slot have a configuration that presents a free play of almost 14°³⁸. The choice of a large cross-section nickel–titanium archwire for torque application, in addition to the problem of free play, is accompanied by another disadvantage in expressing the full range of torque prescribed in the bracket: the decreased stiffness of the wire relative to the stainless steel alloy⁴⁴. The lack of stiffness for nickel–titanium wires has been reported to account for the requirement that wire torque exceed 25° in order to induce a deactivation plateau³⁷. Because such high torque values cannot be found in any prescription, it is postulated that the clinical efficiency of low-modulus wires in delivering torque is questionable if no wire twisting is incorporated, where this is applicable, i.e. in β -titanium wires. Alternatively, a reverse curve of Spee wire configuration may counteract the disadvantage of poor torsional stiffness of a nickel–titanium archwire, enhancing its performance; this was applied during treatment. It is important to note that it is doubtful that the Damon2 bracket, especially in extraction cases, would have been able to deliver comparable torque to the conventionally ligated brackets in the case where reverse curve archwires had not been used. The lack of friction and the increased play determined by the wire–slot interaction with a passive self-ligating bracket would have allowed retroclination of maxillary incisors, a clinical finding often present in extraction cases. The Damon system comes in low (7°), standard (10°) and high torque (17°) prescriptions to accommodate various cases. However, no study exists which clinically evaluates the delivery of torque of the various

prescriptions. It is the belief of the authors that almost all cases are better off with the high torque prescription to counteract and minimize the torque delivery disadvantages of passive self-ligation.

Finally, Pandis *et al.*⁴⁵ evaluated the changes in the mechanical properties of the ligating clip following use for two active self-ligating brackets (In-Ovation R and SPEED); an analytical treatment of this issue is provided in Chapter 3. Significantly reduced clip stiffness was found for the In-Ovation R compared with the SPEED bracket. The above findings may inadvertently affect the force/torque delivery during the final stages of treatment when heavier wires are engaged. The variability observed between the two products tested may reflect differences in composition and manufacturing process for these two brackets, and its effect on bracket–archwire engagement should be further explored.

SPACE CLOSURE

At the time of the publication of this book in the only available study on space closure, Miles⁴⁶ evaluated the rate of en masse retraction with sliding mechanics between passive self-ligating SmartClip brackets and conventional twin brackets ligated with stainless steel ligatures. Thirteen patients with 14 arches completed this prospective trial with 0.018" slot brackets. All patients had first premolar extractions with the second premolar and the first molar distal to the extraction site bonded with SmartClip brackets on one side and conventional twin brackets on the other, with the sides alternated for each consecutive patient. Space closure was achieved on 0.016" × 0.022" stainless steel wires with nickel–titanium coil springs activated from 6–9 mm. The median rates of tooth movement were similar, with the SmartClip bracket side being 1.1 mm per month and the conventional twin bracket side 1.2 mm per month. The argument can be made that the archwire cannot slide toward the ‘free’ sliding self-ligating bracket side making the slower side the rate-limiting factor in space closure. Using an archwire with the post close to the distal of the lateral incisors prevents any sliding of the archwire in the anterior section. In this study the six anterior teeth were ligated from canine to canine and therefore any sliding of the archwire through the brackets is solely occurring through the brackets distal to the

extraction spaces. In this case there are three possible scenarios if there is a difference in the rate of space closure: (1) teeth distal to the extraction site move mesially faster, (2) the midline/archform skews to the side with faster movement, or (3) both occur. In all cases, a difference would have been detected in this split-mouth study design. As no difference in the rate of space closure and no midline skewing was reported, it suggests that either the physiology was the major determinant in the rate of tooth movement, or, if friction was a factor, there was no significant difference between using a steel ligature and a passive self-ligating bracket.

Using a 0.016" × 0.016" stainless steel wire in a 0.018" slot conventional twin bracket, Bokas and Woods⁴⁷ evaluated space closure in a split-mouth design. They tied either a chain or coil spring from the first molar and activated it to deliver ~200 g force when tying it to the distal wing of the canine bracket with a steel ligature. They reported the rate of canine retraction using nickel–titanium springs was 1.9 mm per month and 1.7 mm per month with chains. Deguchi *et al.*⁴⁸ also used a split-mouth design to evaluate canine retraction on a 0.016" stainless steel wire in plastic 0.018" brackets with a metal slot insert. The teeth on one side were ligated with a ‘passive’ clip insert while the other side was ligated with a steel ligature. Three different spring forces were compared (50 g, 100 g, 150 g) in a small sample of 10 subjects in each group, and they found ~1.5 times faster retraction of the canines in the experimental group using the clip method of ligation. The rate of retraction with the 100 g springs was 1.8 mm per month with clip ligation, the same as reported by Bokas, but only 1.2 mm per month on the side ligated with a steel ligature over both wings. The archwire was ligated over both wings with a steel ligature in this study so perhaps tying over both wings when retracting a canine affected canine retraction when compared with the one wing as used by Bokas and Woods in their study. As the lower force level of only 50 g was still very effective in retracting the canine with the clip mechanism, the suggestion could be made that the higher force levels used by Bokas and Woods would then increase the anchorage loading upon the teeth distal to the extraction site and therefore result in greater anchorage loss. However, as stated by Southard *et al.*⁴⁹, a frictional force placed upon a canine must compress the archwire between the canine and molar resulting

in an equal and opposite force being applied distally to the molar teeth. The frictional force reducing the force of retraction on the canine must equally reduce the force of protraction on the teeth distal to the extraction site. Therefore, self-ligating brackets would have no influence on anchorage loading.

In conclusion, the limited current evidence does not support the notion that self-ligating systems deliver faster space consolidation, whilst lower friction and faster tooth movement *in vitro* are not necessarily translated into faster tooth movement *in vivo*. Further studies in the form of randomized clinical trials are needed.

HANDLING EFFICIENCY

A number of studies have explored the efficiency of archwire changes with self-ligating brackets. Shivapuja and Berger⁵⁰ evaluated Activa ('A' Company, Johnson & Johnson, San Diego, CA), Edgelok (Ormco, Glendora, CA) and SPEED self-ligating bracket systems. They concluded that dramatically less chairtime for archwire removal and insertion is required compared to the conventional bracket systems. On the contrary, Harradine¹⁹ found insignificant time savings in regard to archwire changes between the Activa self-ligating bracket and the conventional edgewise bracket. In 2000, Berger and Byloff¹⁰ conducted a mail survey of orthodontists and from the responses concluded that stainless steel ligatures required about 6 or 7 minutes per arch, and elastomeric ligatures nearly 2 minutes per arch. The total opening and closing time per arch was less than 1 minute for each of the four self-ligating bracket designs, with the SPEED system taking the least average time and the Damon the most. Opening and closing times were similar in both arches for all the self-ligating brackets except the TwinLock (Ormco). Turnbull and Birnie⁵¹ assessed the relative speed of archwire changes, comparing the Damon2 self-ligating brackets with conventional elastomeric ligation methods, and further assessed this in relation to the stage of orthodontic treatment represented by different wire sizes and types. They found that the Damon2 self-ligating system had a significantly shorter mean archwire ligation time for both placing and removing wires compared with the conventional elastomeric system. Ligation of an archwire was approximately twice as quick with the

self-ligating system. This difference in ligation time between the Damon2 and the conventional mini-twin brackets became more marked for larger wire sizes used in later treatment stages. It is important to note that with the heavy emphasis on the research and development of self-ligating brackets, improvements in design will further optimize the handling characteristics of these appliances.

DISCOMFORT

Discomfort is a potential side effect during fixed appliance orthodontic therapy and may influence the treatment outcome and the desire to undergo treatment^{52–56}. A potentially important factor is the amount of force applied to the dentition by the orthodontic archwire, with early histological studies suggesting that light orthodontic forces are more efficient and less traumatic⁵⁷. Therefore, the use of increased force levels, potentially related with higher crowding, might be expected to be associated with increased discomfort. It has been shown that perceived pain peaks at around 24 hours after initial archwire placement, with reducing levels during the subsequent week. However, a clear and direct relationship between applied force and perceived pain is not clearly defined^{58–62}.

Miles *et al.*²¹ evaluated the difference in discomfort levels of conventional brackets and the Damon2 brackets within the first few days of archwire placement and again at the first archwire change. Comfort on the lips, preferred look and bracket failure rates were also recorded. The standard bracket was more uncomfortable with the initial archwire ($p = 0.04$). However, at 10 weeks, substantially more patients reported discomfort with the Damon2 bracket when engaging the archwire ($p = 0.004$). His conclusions were that initially the Damon2 bracket was less painful, but it was substantially more painful when placing the second archwire, likely due to the greater irregularity. Alternatively, the discomfort with the second wire was assessed immediately after wire placement, so the ligation process and experience of the operator placing the wire could also influence this result. The above findings are in accordance with the authors' *in vitro* study where the moments generated during engagement of the $0.014'' \times 0.025''$ copper–nickel–titanium were much higher for the Damon2 bracket compared to the conventional and

the In-Ovation R bracket⁶³. The explanation lies with the fact that in order to close the slot with the Damon bracket system the wire needs to be fully seated at the bracket slot, whereas on the two other brackets the elasticity of the 'O' rings and nickel–titanium clip allow for some moment dissipation.

Fleming *et al.*⁶⁴ evaluated difference in the pain experienced during removal and insertion of orthodontic archwires between SmartClip self-ligating brackets and a conventional Victory appliance. After appliance placement and engagement of a 0.016" nickel–titanium archwire, pain experience was recorded at 4, 24 and 72 hours and 7 days with a visual analog scale (VAS) questionnaire. At a subsequent visit, participants documented pain experiences during removal and insertion of 0.019" × 0.025" archwires on an additional 100 mm VAS questionnaire. They found that bracket type had no influence on pain experience at all times following placement of the 0.016" nickel–titanium archwire. However, significantly greater discomfort was experienced during archwire insertion and removal of the 0.019" × 0.025" wire with the SmartClip appliance. Recently the SmartClip bracket clip has been refined to reduce the required engagement force levels. Also wires with rounded corners are recommended, which would be expected to be more comfortable although some reduction in torque control may be a consequence.

Scott *et al.*⁶⁵ compared the degree of discomfort experienced during the period of initial orthodontic tooth movement using Damon3 self-ligating and Synthesis conventional ligating pre-adjusted bracket systems. A two-center study included 62 subjects with lower incisor irregularity between 5 and 12 mm treated with first premolar extractions. Following insertion of 0.014" copper–nickel–titanium Damon archwires, the subjects were given a prepared discomfort diary to complete over the first week, recording discomfort using a VAS at various time intervals. The researchers found no evidence to suggest that Damon3 self-ligating brackets were associated with less discomfort than conventional pre-adjusted brackets during initial tooth alignment. It should be emphasized here that comparisons were made only with round 0.014" nickel–titanium wires.

Finally, Pringle *et al.*⁶⁶, utilizing a 0.014" copper–nickel–titanium wire, compared pain intensity levels between patients bonded with conventional and

Damon3 self-ligating brackets during the first week of treatment. Although there was inter-individual variation, patients in the Damon group reported lower mean pain by an amount considered clinically insignificant. However, the mean pain intensity was significantly lower in the Damon3 group ($p = 0.012$) compared to the conventional group. Some important points regarding this study are:

- Treatment was carried out by seven operators, a fact that could possibly introduce a confounding variable
- Sample included adults and adolescents, possibly introducing variability in pain perception between age groups⁶²
- Pain levels were evaluated only with 0.014" copper–nickel–titanium wire, whereas Miles *et al.*²¹ evaluated pain levels also after insertion of rectangular nickel–titanium wires

An *in vitro* study⁶⁷ comparing initial forces levels generated after the insertion of a 0.014" copper–nickel–titanium wire in a conventional, a Damon2 and In-Ovation R set-up concluded that:

- Variation of force levels among the three brackets tested follows a complex pattern and seems to be influenced by multiple factors such as ligation mechanism, bracket width, arch form and tooth position, each contributing with variable weighting depending on the specific characteristics of the arch and the wire
- Force levels generated varied with the direction of movement and were not consistent with a bracket type, thus rendering questionable the notion that the free play of a passive self-ligating bracket automatically means lower force levels compared to a conventional bracket–wire–elastic set-up

Again, there is no conclusive evidence to support significant differences in pain levels between conventional and self-ligating brackets.

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7

Root Resorption in Orthodontics

M. Ali Darendeliler and Lam L. Cheng

INTRODUCTION

Root resorption has been studied extensively for over a century. It is a physiological or pathological process that results in a loss of substance from mineralized cementum and dentine^{1,2}. External root resorption (ERR) in orthodontics is a pathological process that seems to be related to the local injury of the periodontal ligament (PDL) which occurs in association with the removal of hyalinized tissue^{3,4}. The contradictory fact is that root resorption is an inflammatory process and this inflammation is required for tooth movement. Therefore, root resorption is commonly known to be an unavoidable adverse effect of orthodontic treatment. Root resorption continues in hyalinized tissue even after active force has been terminated⁵. However, a reparative process in the periodontium commences when the applied orthodontic force is discontinued or reduced below a certain level^{6,7}. This healing process can occur as early as the first week of retention following orthodontic treatment and increases over time⁸⁻¹⁰. There are biological and mechanical factors that influence the severity of orthodontically induced inflammatory root resorption (OIIRR). Mechanical causative factors can be controlled by the clinician to minimize the adverse effect of root resorption and allow initiation of repair. The majority of root resorption studies were achieved two dimensionally through radiographs¹¹, light microscopy¹², scanning electron microscopy (SEM)⁸ and transmission electron microscopy (TEM)¹³. Three-dimensional (3D) methods including stereo SEM imaging and X-ray microtomography (XMT) are more accurate and reliable quantitative measuring tools in root resorption studies¹⁴⁻¹⁶.

HISTORY OF OIIRR

Root resorption of permanent teeth was first discussed by Bates in 1856 as a process referred to as ‘absorption’ due to traumatization of periodontal membrane¹⁷. In 1914, Ottolengui¹⁸ identified root resorption that was specifically caused by orthodontic treatment. Later, Ketcham¹⁹ reported through a radiographic study that root shortening could be an anatomical variation, a result of impaction or orthodontic treatment. Ketcham²⁰ also suggested that hormonal imbalance and dietary deficiencies were possible reasons for the occurrence of root resorption. During that era, both absorption and resorption were used to describe the loss of apical root material. It was not until 1932, that Becks and Marshall²¹ suggested the use of resorption instead of absorption because ‘in all cases in which formed tissues are destroyed and taken up by the blood or lymph stream, one should, in medical or dental literature, speak only of resorption’.

INCIDENCE OF OIIRR

Root resorption occurs in most individuals following orthodontic tooth movement. Lupi *et al.*²² investigated a sample of 88 ethnically and racially diverse adults radiographically and revealed that 15% of the teeth had resorption prior to orthodontic treatment. After 12 months of orthodontic treatment, the incidence of OIIRR increased to 73%. In a larger study of more than 868 cases, >2 mm of external apical root resorption (EARR) was seen in 25% of treatment patients²³. Fortunately, only up to 5% of

individuals suffer from severe root resorption (i.e. >5 mm of root loss)^{24–26}.

LOCATION OF OIIRR

The distribution of root resorption is dictated by the pressure zone created by different types of tooth movement. Stenvik and Mjor²⁷ found 60% of teeth had evidence of resorption of cementum and dentine and the distribution in the marginal and apical parts of the tooth was the same. However, OIIRR tends to occur preferentially in the apical region because the fulcrum of most tooth movement is usually occlusal to the apical half of the root (Fig. 7.1)²⁸. In addition, the orientation of the periodontal fibres at the apical end is different, which increases the stress in the region²⁹, and the apical third of the root is covered by the more friable acellular cementum^{28–30}.

SEVERITY OF OIIRR

Brezniak and Wasserstein³¹ have illustrated three levels of OIIRR severity:

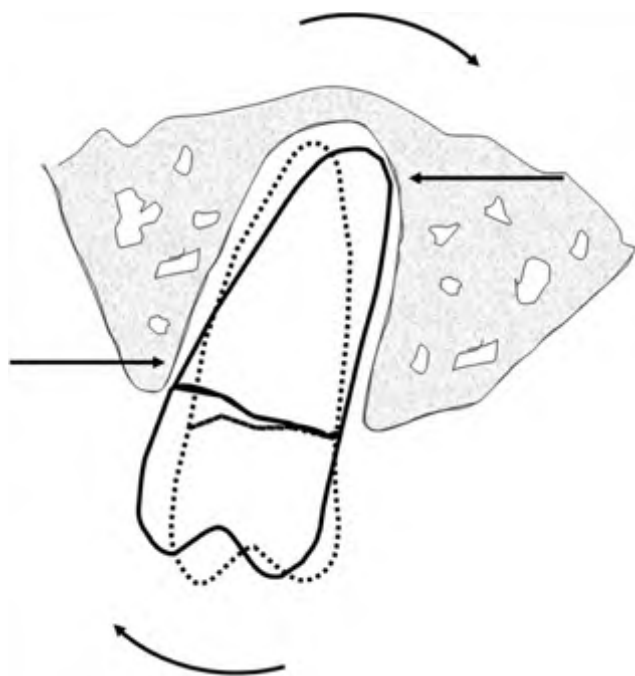


Fig. 7.1 Compression and tension zones in the PDL will depend on the moment and type of tooth movement. Figure shows the compression areas in case of buccally tipping movement.

- Cemental or surface resorption with remodeling. This type of OIIRR is similar to trabecular bone remodeling in which the resorbed cemental layers are fully regenerated or remodeled
- Dentinal resorption with repair. The resorbed cementum and the outer layers of the dentine are repaired with cementum material which may or may not restore the root to its original size and shape
- Circumferential apical root resorption. Significant resorption of the root apex results in root shortening with no evidence of regeneration. However, with time the sharp edges formed by resorption craters may be leveled. Surface reparation only occurs in the cemental layer

DIAGNOSIS OF OIIRR

Radiographs have been widely used to clinically diagnose OIIRR. Dental panoramic tomography (DPT) provides an overall view of the dentition with lower radiation dose than a full-mouth series of intraoral radiographs³². However, due to the narrowness of the focal trough, the apices and palatal structures can be out of focus in the incisor region. Therefore, additional radiographs such as periapical radiographs or occlusographs may be needed to supplement the DPT. Paralleling technique for periapical radiograph is preferable as it provides a geometrically accurate image and, together with the use of a film holder and aiming device, radiographs can be standardized in two different time points. The two-dimensional (2D) nature of radiography limits its accuracy because buccal and lingual root defects are not detectable³⁴. Computed tomographic scanning offers a significant advantage over conventional radiography in the detection and quantification of root resorption. However, its high cost and high radiation exposure to the patient limit its use mainly to *in vitro* research.

PATHOGENESIS OF OIIRR

OIIRR is associated with local overcompression of the PDL which results in an aseptic coagulation necrosis process, i.e. hyalinization. Resorption of the cementum occurs simultaneously with the removal of hyalinized tissue^{6,36–38}. It starts at the periphery of

the hyalinized periodontal membrane which is followed by resorption of surrounding root and bone surfaces^{4,39} and invasion of blood vessels¹². The resorption process propagates until no hyalinized tissue is present and/or the force level diminishes. The resorption crater expands the root surfaces involved and thereby indirectly decreases the pressure exerted through force application. Decompression causes the process to reverse and the cementum reparative process begins. The resorbing areas on a root surface may show signs of concurrent active resorption and repair^{8,27}.

LIGHT MICROSCOPY OF OIIRR

Brudvik and Rygh^{4,12} have performed extensive rodent research on the histological sequence of root resorption and repair under light microscopy and TEM. These studies have shown that cellular activities within the periodontal apparatus vary with time and location. The process of OIIRR was described as three sequences of events in two different locations, periphery and main hyalinized zones:

1. Tartrate resistant acid phosphatase (TRAP)-negative mono-nucleated fibroblast-like cells

initiated root resorption from the periphery of the main hyalinized zone by the nearest viable cells in the presence of adequate vascularity

2. TRAP-positive multinucleated cells participated in the removal of the main hyalinized tissue and resorption of the adjacent root structure. This only occurred after elimination of a considerable amount of hyalinized tissue between alveolar bone and the root surface and continued even after the initial root resorption had terminated. The cells involved during this resorptive phase were derived from adjacent marrow spaces
3. Active root resorption continued in areas of hyalinized tissue even after orthodontic force had ceased. The reparative process occurred from the periphery of the resorption craters and extended to the central part

SCANNING ELECTRON MICROSCOPY OF OIIRR

Enhanced visual and perspective assessment of OIIRR can be achieved by SEM (Fig. 7.2). SEM also allows 2D measurement of resorption craters using surface area landmarks. Chan *et al.*⁴⁰ compared 2D versus 3D measurements of the root resorption craters over 28 days with SEM and demonstrated

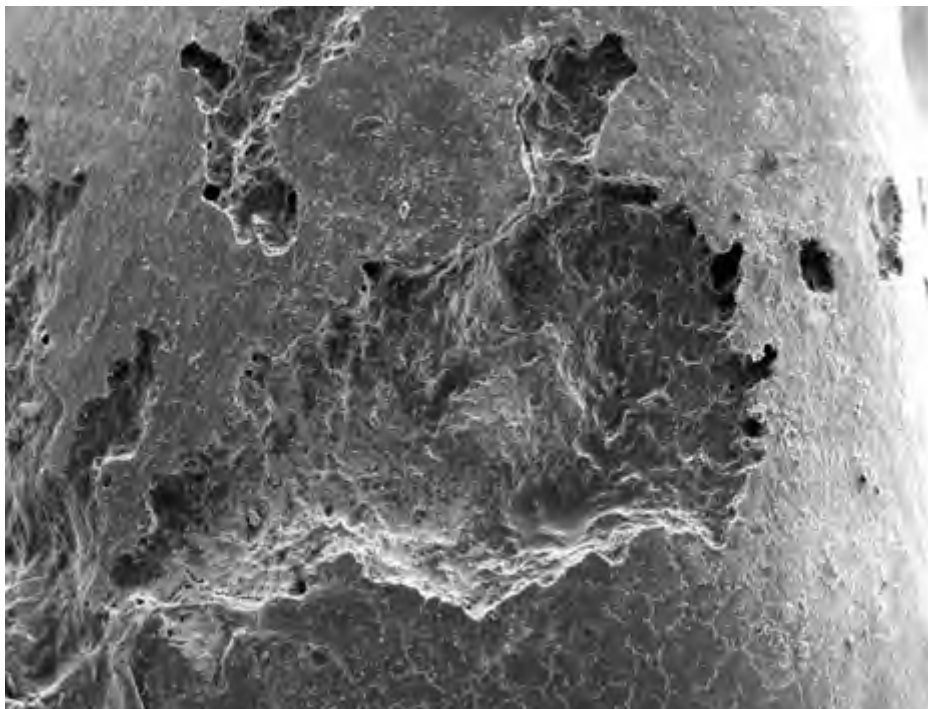


Fig. 7.2 2D scanning electronmicroscope image of a root resorption crater.

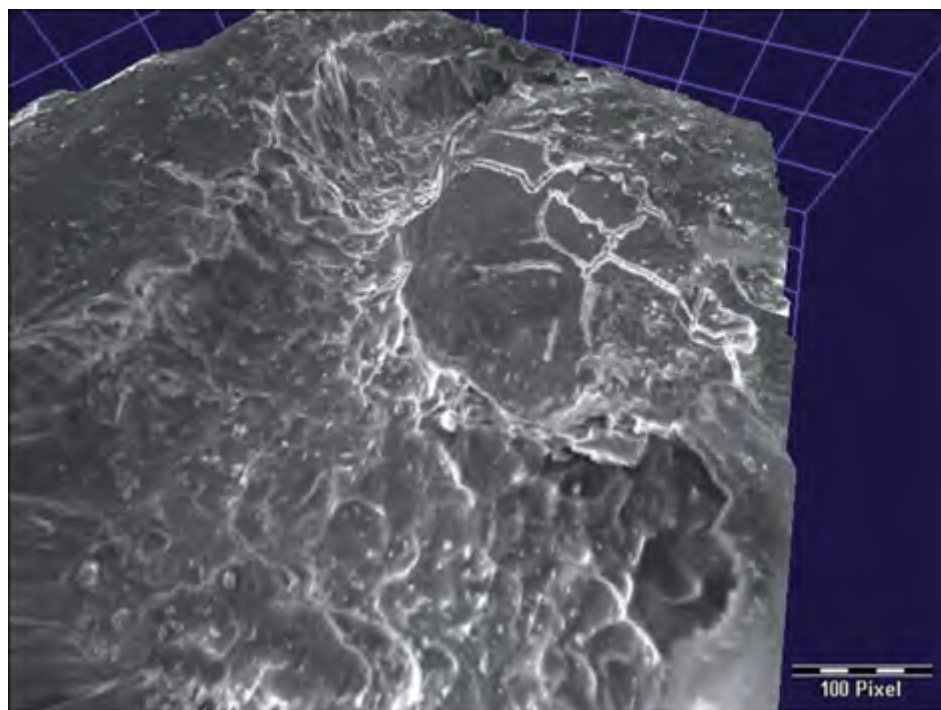


Fig. 7.3 3D simulation image of a root resorption crater obtained using SEM stereo imaging technique.

no significant difference even though 2D measurements were made on the curved root surfaces (Fig. 7.3). However, longer treatment times may show a difference between 2D and 3D measurements due to increase in depth of the craters.

Kvam³⁷ was one of the earlier investigators who utilized SEM to depict and measure root resorption craters. Marginal root resorption began at 10 days and root resorption craters initiated as small cavities with diameters of 6 μm . As resorption progresses, the number of small, round and thin-walled craters increased and merged into extensive and shallow craters. Latticed fibres appeared on the resorption surfaces of the active resorption sites indicating that the inorganic minerals were removed prior to the collagen component of dentine and cementum. Harry and Sims⁴¹ discovered that progressive apical resorption accompanied by regions of cellular cementum repair was found after 70 days of force application on bicuspid. Barber and Sims⁸ examined the topography of root resorption craters when the human teeth were moved by rapid maxillary expansion (RME) appliances. Actively resorbing surfaces were smooth and multilocular in appearance and were delineated by a rim of relatively sheer and undermined cementum. Resorbing dentine was easily distinguished from resorbing cementum due

to the presence of minute surface openings demarcating sites previously occupied by odontoblastic processes.

Chan *et al.*⁴⁴ quantitatively measured the amount of root resorption subjected to both light and heavy orthodontic forces for 4 weeks by the means of stereo SEM images (Fig. 7.4). The mean volume of root resorption was more than threefold greater in the heavy force group when compared to the light force group.

BIOCHEMISTRY AND MOLECULAR BIOLOGY RELATED TO OIIRR

Resorption activity in response to mechanical or chemical stimuli by the cells of the PDL is characterized by the synthesis of prostaglandin E₂ (PGE₂) with a concomitant increase in cyclic adenosine monophosphate⁴⁵. This process is regulated by hormones (parathyroid^{45,46} and calcitonin^{46,47}), neurotransmitters (substance P⁴⁸, vasoactive intestinal peptide⁴⁹ and calcitonin-gene related peptide⁵⁰) and cytokines or monokines (interleukin-1-alpha^{46,50}, interleukin-1 beta (IL-1 β)^{51,52}, interleukin-2⁵³, tumor necrosis factor (TNF)^{46,53} and interferon-gamma⁵⁴.

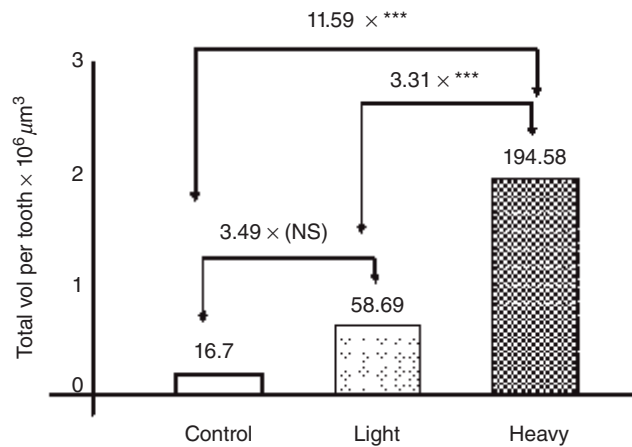


Fig. 7.4 Amount of root resorption following 4 weeks of buccally directed force application using light (25 g) and heavy (225 g) orthodontic forces.

It has also been shown that the osteoclasts are controlled by osteoblasts in many ways.

Recent studies have shown the role of osteoprotegerin (OPG) and receptor activator of nuclear factor kappa B ligand (RANKL) in osteoclastogenesis⁵⁵ and hence the possibility of their role in root resorption⁵⁶. An increase in RANKL and a decrease in the level of OPG expression were found in physiological root resorption in deciduous human teeth. Low *et al.*⁵⁷ investigated the role of OPG and RANKL in artificially induced root resorption in a rat model. Tooth movement was induced by heavy forces and reported an increased level of both RANKL and OPG at sites adjacent to resorption zones compared to the control teeth with no resorption. Recently, Yamaguchi *et al.*⁵⁸ investigated the effect of compressive force on the production of RANKL and OPG. The findings revealed an increase of RANKL and a decrease of OPG in the severe root resorption group. Kojima *et al.*⁵⁹ have shown that substance P stimulated the production of PGE_2 and RANKL which may be responsible for OIIRR.

PHYSICAL PROPERTIES OF ORTHODONTICALLY INDUCED INFLAMMATORY ROOT RESORBED CEMENTUM

Cementum at the cervical and middle thirds of the root has greater hardness and elastic modulus than

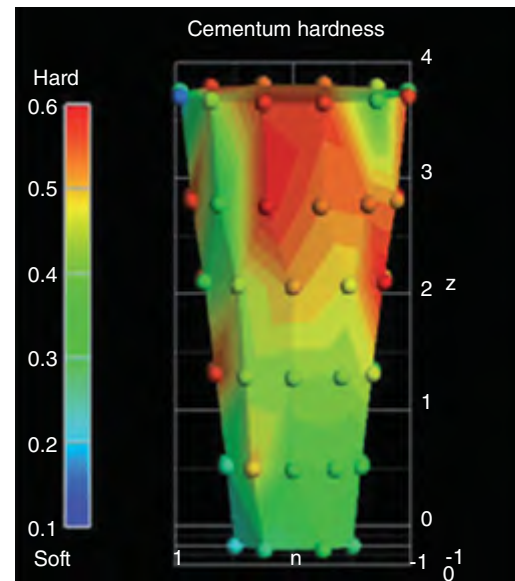


Fig. 7.5 Color-coded mapping of the hardness of the root cementum.

that of the apical third (Fig. 7.5)^{60,61}. This is because of the variable mineral content of cellular and acellular cementum. Chutimanutskul⁶² conducted a study that assessed the relationship between the magnitude of orthodontic forces and physical properties of the human cementum. The study revealed the mean hardness and elastic modulus of cementum was greater in the light force group than the heavy force group. The mean hardness and elastic modulus of cementum gradually decreased from the cervical to apical regions as observed in previous studies^{60,61}. This study concluded that the hardness and elastic modulus of cementum were affected by the application of orthodontic forces.

Rex *et al.*⁶³ studied the mineral composition (calcium (Ca), phosphorus (P) and fluoride(F)) of human premolar cementum following the application of orthodontic forces. The results showed limited change in the mineral composition of cementum after the application of light force. There was a trend towards an increase in the Ca and P concentration of cementum at various areas of PDL compression. The application of heavy force caused a significant decrease in the Ca concentration of cementum at certain areas of PDL tension. Orthodontic force did not appear to influence the F concentrations in cementum.

FACTORS AFFECTING OIIRR

OIIRR can be influenced by a wide range of shared biological and/or mechanical factors. Biological factors include those that are not within the control of the clinician and are directly related to the patient. Some of these factors may be within the control of the patient which indicates that they can be environmental or genetic in origin. Mechanical factors are attributed to the nature of the orthodontic appliance and could be controlled by both the clinician and the patient.

Biological factors

Genetic factors

Root resorption can occur in normal individuals without orthodontic treatment, which illustrates the individual susceptibility to root resorption²⁹. In fact, root resorption is related to one's tissue response and metabolic activity. Metabolic signals (e.g. hormones, body type and metabolic rate) influence the relationship between osteoblastic and osteoclastic activity which modifies cell metabolism, an individual's reaction pattern to disease, trauma and aging⁶. Root resorption can vary among individuals and within the same person at different times.

Genetic influence on the susceptibility to root resorption remains controversial. Harris *et al.*⁶⁵ investigated the genetic influence on EARR by using a sib-pair model and reported 70% heritability for resorption of maxillary incisor roots and the mesial and distal roots of the mandibular first molars. This accounted for approximately half of the total phenotypic variation⁶⁵. This meant that siblings experienced similar levels of EARR in response to orthodontic treatment. A recent study has also revealed a familial association of OIIRR⁶⁶.

Al-Qawasmi *et al.*⁶⁷ identified a key role of IL-1 β gene polymorphism for a genetic influence in EARR in orthodontically treated individuals. Individuals homozygous for the IL-1 β (+3953) allele 1 had a 5.6-fold increased risk of EARR >2 mm as compared with individuals who are not homozygous for the IL-1 β (+3953) allele 1. This polymorphism accounted for approximately 15% of variation in EARR of upper centrals. Another candidate gene for EARR is TNFRSF11A, which encodes the receptor

activator nuclear factor-kappa B, an essential signaling molecule in osteoclast formation and activation⁶⁹.

One of the difficulties in assessing the genetic contribution to OIIRR is the ability to separate genetic factors from environmental factors such as orthodontic treatment⁷⁰. Ngan *et al.*⁷⁰ investigated the genetic contribution to OIIRR by retrospectively assessing the pre- and post-treatment records of 16 monozygotic and 10 dizygotic twins. Each twin pair had the same malocclusion and the same type of appliance treatment with the same clinician. DPT tooth root measurements were used to obtain quantitative and qualitative estimates of concordance for EARR. The concordance estimate for root resorption in monozygotic twins was 44.9% for qualitative measurements and 49.2% for quantitative measurements. The concordance estimate for root resorption in dizygotic twins was 24.7% for qualitative measurements and 28.3% for quantitative measurements. The authors thus confirmed the presence of a genetic component to OIIRR. However, they advised that a larger sample was required before a model of heritability could be used to determine the components contributing to the variance⁷⁰.

Ethnicity can also influence the susceptibility to OIIRR. Sameshima and Sinclair²³ have found that Caucasians and Hispanics were more prone to OIIRR than Asians.

Environmental factors

Asthma and allergy

There was an increased incidence of OIIRR, especially blunting of maxillary molars, found in patients with chronic asthma^{71,72}. This could be attributed to the close proximity of the roots to the inflamed maxillary sinus and or the presence of inflammatory mediators in these patients. McNab *et al.*⁷¹ reported an elevated incidence of EARR in the asthma group but both asthmatics and healthy patients exhibited similar amounts of moderate and severe root resorption. This implied that the increased incidence of EARR in asthmatics was confined to an increase in root blunting. Therefore, asthmatics had only a minimal risk to posterior EARR that may not adversely affect the function or longevity of the posterior teeth.

Allergy may increase the risk of OIIRR^{72,73}. Nishio *et al.*⁷⁴ investigated the association between excessive root resorption and immune system factors in a sample of Japanese orthodontic patients. The result showed that the incidence of allergy, asthma and root morphology abnormality was significantly higher in the root resorption group.

Corticosteroids are commonly used to treat allergy, asthma, dermatitis and eczema. Research on the effect of orthodontic treatment under corticosteroid treatment on root resorption remains controversial. This could be due to different dosages of corticosteroids used and also different animal models studied⁷⁹. Recently, Verna *et al.*⁷⁹ investigated the effect of acute and chronic corticosteroid treatment on OIIRR. The results showed more root resorption in the acute treatment group on the mesial coronal level than chronic treatment and control groups. The less resorption found in the chronic group may be due to faster remodeling of bone, less hyalinization and less remodeling of root tissue.

Endocrine and hormone imbalance

The endocrine system is closely related to bone activity and metabolism. Imbalance of the endocrine system due to hypothyroidism, hypopituitarism, hyperpituitarism, hyperparathyroidism⁸⁰, Paget's disease⁸¹ and hypophosphatemia⁸² are hypothesized to be related to OIIRR^{80,83,84}. An excess of thyroid hormones which increased bone turnover were found to reduce root resorption during orthodontic tooth displacement in a rat model⁸⁵. However, hypothyroidism has been associated with increased root resorption in the absence of orthodontic load⁸⁶.

Calcitonin can inhibit odontoclast activity⁸⁷. The action of calcitonin on osteoclasts occurs at later stages of osteoclast development and it inhibits the fusion of pre-osteoclasts to form mature multinucleated cells.

Alcohol consumption

The presence of ethanol in the circulation inhibits the hydroxylation of vitamin D3 in the liver, thus hindering calcium homeostasis and resulting in a rise in parathyroid hormone (PTH). PTH in turn enhances the resorption of mineralized tissues including tooth roots. It has thus been suggested that

chronic alcohol consumption during orthodontic treatment increases the risk of severe OIIRR⁷³.

Nutrition

Root resorption has been demonstrated in animals deprived of dietary calcium and vitamin D^{80,84}. Engstrom *et al.*⁸⁰ found the experimental rat group that was fed with a diet deficient in calcium and vitamin D had hypocalcemia, increased alkaline phosphatase activity and increased circulating PTH when compared to the control group which was fed with a normal diet. Orthodontic tooth movement produced greater and more rapid bone resorption and more severe OIIRR in the experimental group. The study also showed an increased number of osteoclasts in the PDL of the test group which was suggested to be due to increased PTH levels.

It has been proposed by other authors that poor nutrition is not a major etiological factor in OIIRR⁸⁸. Goldie and King⁸⁸ deprived lactating rats of dietary calcium and phosphorus and compared them with a control group on a normal laboratory diet. Despite a greater amount of tooth movement and loss of bone mass in the dietary deficient group, the OIIRR craters were smaller.

Drugs

Inhibiting cyclo-oxygenase and the subsequent production of prostaglandins with non-steroidal anti-inflammatory drugs (NSAIDs) can be useful in decreasing bone and root resorption. Villa *et al.*⁸⁹ investigated the effect of nabumetone, a type of NSAID, on root resorption during intrusive orthodontic tooth movement, and showed less root resorption when patients received nabumetone and that the drug did not impede tooth movement. This was supported by Kameyama *et al.*⁹⁰ in which the rats were prescribed aspirin which led to a suppression of root resorption caused by mechanical injury.

Bisphosphonates directly or indirectly induce apoptosis in osteoclasts which play a role in the inhibition of bone resorption⁹¹. Liu *et al.*⁹² investigated the effect of clodronate, a non-nitrogen containing bisphosphonate, on orthodontic tooth movement and root resorption in rats and found tooth movement was less, number of osteoclasts decreased and root resorptive area was smaller.

Clodronate may have either inhibited recruitment of osteoclasts or promoted osteoclast apoptosis⁹³. Clodronate has also been shown to inhibit the production or release of pro-inflammatory molecules in macrophages and/or osteoblastic cells^{94–98}.

Chronological age

The aging process results in changes to the hard and soft tissues of the dentoalveolus. The periodontal membrane becomes aplastic, narrow and less vascular with age. The bone becomes denser, avascular and aplastic and the thickness of cementum increases⁷. Adults are also exposed to previous orthodontic treatment and inflammation associated with endodontically treated teeth or traumatized teeth which predisposes them to OIIRR^{99,100}.

Mirabella and Artun²⁶ evaluated a large sample of adult patients for their prevalence and severity of OIIRR in maxillary anterior teeth: 40% of the adults had one or more teeth with ≥ 2.5 mm resorption. This indicated that the sample of adults had a higher mean value of severely resorbed tooth per patient than the comparable group of adolescents, which was 16.5%⁹⁹. On the other hand, Harris and Baker¹⁰¹ reported that 61% of the adult patients had some degree of resorption after orthodontic treatment which was not significantly different from the 58% of adolescent patients experiencing root resorption in that same study. Linge and Linge⁹⁹ found less resorption in patients treated before the age of 11. They suggested that resorption could be avoided if tooth movement was completed before the roots were fully developed, before the age of 11.5 years, but treatment at this age was impossible for many patients.

Dental age

Partially formed roots have been found to develop normally during orthodontic treatment and it has been suggested that teeth with open apices may be more resistant to ERR^{99,102–104}. Mavragani *et al.*¹⁰⁵ investigated root lengthening during orthodontic treatment in relation to the age of patient, the developmental stage of the root and the anticipated growth. Results revealed a definite advantage for younger teeth with regards to post-treatment root length.

Gender

Some studies have suggested that orthodontically treated females had a greater incidence of OIIRR than males^{64,106–108}. Newman⁶⁴ found a ratio of OIIRR susceptibility of 3.7:1 for females to males respectively. Dougherty¹⁰⁹ suggested that this finding might be due to the differences in root maturity between males and females at the age of tooth movement. Few studies have shown the opposite, that males have higher incidence of OIIRR than females^{30,110}. However, most of the studies have found no correlation between gender and the extent of OIIRR^{23,28,65,111–114}.

Local factors

Habits

A number of habits have been reported to result in an increased risk of OIIRR. Finger sucking beyond the age of 7 years has been suggested to be a risk factor⁹⁹. Nail-biting¹¹⁵, forward tongue pressure and tongue thrust^{64,99} were also proposed to be linked. Some studies^{116,117} found that the root resorption was significantly higher before orthodontic treatment in nail-biting patients whereas others¹⁰⁴ found no greater incidence of root resorption in nail-biting patients. Long-term orthopedic tongue thrusting forces which result in anterior open bite may promote root resorption¹¹⁸, particularly when vertical elastics are used in an attempt to close open bites associated with tongue problems.

History of trauma

Orthodontic tooth movement of a severely traumatized tooth may result in increased resorption^{99,104,119–121}. Linge and Linge¹⁰⁴ found that teeth which had previous trauma had an average loss of root structure after orthodontic movement of 1.07 mm compared with a loss of 0.64 mm for untraumatized teeth. However, Kjaer¹⁰⁷ proposed that teeth with slight or moderate injuries may not have any greater tendency towards OIIRR than uninjured teeth. Malmgren *et al.*¹²⁰ suggested a waiting period of 1 year after a traumatic incident before the initiation of orthodontic tooth movement.

Density and turnover of alveolar bone

It has been suggested that OIIRR was amplified in dense alveolar bone compared to less dense alveolar bone, especially if there was an increased number of resorptive cells associated with the increased number of marrow spaces^{7,38}. Reitan³⁸ proposed that a strong continuous force on low density alveolar bone caused an equivalent amount of OIIRR to that of a mild continuous force on high density alveolar bone.

Verna *et al.*¹²⁴ investigated the impact of bone turnover rate on the amount of tooth movement and the incidence of OIIRR in rats. High bone turnover increased the amount of tooth movement compared with the normal or low bone turnover state. The untreated side in the low bone turnover group showed more root resorption suggesting that in clinical situations where turnover of alveolar bone was delayed, root surfaces could already be affected by root resorption at baseline condition.

Maxilla and mandible

A recent comparative study has shown that 12 weeks of buccally directed orthodontic forces caused marginally more root resorption on the maxillary first premolars than mandibular first premolars¹²⁵. This could be a result of the greater recruitment of inflammatory cells near the maxillary sinus.

Types of malocclusion

A number of studies have found a relationship between OIIRR and malocclusion^{23,65,99,118}. Severe malocclusion requires greater tooth movement, for example, greater overjet requires greater retraction and deeper overbite needs greater intrusion^{65,111}; hence, there will be a greater amount of root resorption.

Kaley and Phillips¹²² reported that class III patients showed severe root resorption with root apex approximation to the palatal cortical plate. They suggested that the maxillary incisors were tipped forward in compensation for the class III jaw relationship which forced the roots against the palatal cortical plate during orthodontic treatment. Class III surgical cases demonstrated 1.6% and 20.8% reduction in maxillary and mandibular incisor lengths respectively¹²². It has been proposed that orthogona-

thic surgery contributed to OIIRR by altering the blood supply and nutrition to the periodontium¹²⁸.

Hypofunctional periodontium

Hypofunctional periodontium results in narrowed periodontal space and derangement of functional fibres which would eliminate the normal cushioning effect of the PDL¹²⁹ thus resulting in a high concentration of force. This leads to stimulation of inflammation by the promotion of inflammatory mediators secreted from local cells to induce destruction of tooth and bone¹³⁰. Sringkarnboriboon *et al.*¹³¹ compared the amount of root resorption associated with a normal and a hypofunctional periodontium in rats during experimental tooth movement caused by heavy continuous force. The results showed the amount of root resorption was significantly greater in teeth with a hypofunctional periodontium than in those with a normal periodontium.

Occlusal trauma

Occlusal trauma from improper occlusion, interfering dental restorations and inadequate prosthetic appliances accelerated root resorption^{132,133}. Functional trauma to individual teeth caused root resorption, however, 85% of these areas showed anatomically complete repair with secondary cementum¹³⁴.

Missing teeth

Patients with multiple tooth aplasia (≥ 4 missing teeth) were more prone to OIIRR, especially teeth with irregular root morphology and protracted treatment with elastics and rectangular arch wires¹³⁵.

Specific tooth vulnerability to root resorption

The teeth most frequently affected by OIIRR according to severity are the maxillary lateral incisors, maxillary central incisors, mandibular incisors, distal root of mandibular first molar, mandibular second premolars and maxillary second premolars^{23,136–138}. Maxillary lateral incisors are more susceptible to root resorption due to the abnormal root shape²³. Maxillary teeth showed a higher incidence of root resorption than mandibular teeth^{19,64,112,139,140}.

Dental invagination

It has been claimed that dental invagination is one of the predisposing factors for OIIRR^{107,141}. However, there is no general agreement concerning the role of dental invagination as a risk factor for orthodontic root resorption. Mavragani *et al.*¹⁴³ investigated the association between dental invagination and root shortening during orthodontic treatment and found invaginated teeth more often exhibited deviated root form which was considered a risk factor for ERR. However, invaginated teeth had delayed development and immature roots which seemed to protect against root resorption¹⁰⁵. They concluded that the mild form of dental invagination confined within the crown and not extending beyond the level of cemento-enamel junction was not a risk factor for ERR.

Abnormal root morphology

The tendency of OIIRR was found to be greater in teeth with aberrant-shaped roots^{11,23,107,144,145}. Recently, Oyama *et al.*¹⁴⁷ investigated the stress distribution at the root apex with a variety of root shapes during orthodontic force application using finite element models. They discovered that short, bent and pipette root shape resulted in a greater loading of the root than normal root shapes during orthodontic force application, which suggested that root deviations tended to promote root resorption.

Root resorption prior to orthodontic treatment

Patients with pre-existing evidence of root resorption have been found to be at greater risk in developing further severe OIIRR with treatment^{116,118}.

Previous endodontic treatment

Conflicting reports remain in the literature regarding the susceptibility of non-vital endodontically treated teeth to OIIRR. One group has found a greater incidence of OIIRR in endodontically treated teeth but the results could be biased as the non-vital teeth were treated endodontically as a result of trauma¹⁴⁸. Spurrier *et al.*¹¹⁰ found vital incisors resorbed to a significantly greater degree than endodontically



Fig. 7.6 Micro-CT image of a maxillary first premolar.

treated incisors. Many other authors believed that endodontically treated teeth were more resistant to root resorption due to an increase in dentine hardness and density^{7,110,139,145}.

Orthodontic tooth movement itself creates an inflammatory response that may increase an already existing resorptive process. A successful endodontically treated tooth with healthy periodontal support, in the absence of inflammation, should not be more susceptible to resorption than a normal tooth. Advanced computed tomography (CT) images promise easier diagnosis and treatment of root canals in the near future (Fig. 7.6).

Mechanical factors

Duration of treatment

Most studies agreed that the severity of OIIRR was directly related to the duration of orthodontic treatment^{111,114,126,136,144,151–154}. Only a limited number of studies disagreed with this finding^{127,140}.

Artun *et al.*¹⁵⁵ evaluated standardized periapical radiographs of the maxillary incisors made before treatment (T1) and at about 6 and 12 months after bracket placement (T2 and T3 respectively) of 2467 patients. The risk of one or more teeth with more than 1.0 mm resorption from T2 to T3 was 3.8 times higher than the risk of one or more teeth with more than 1.0 mm resorption from T1 to T2.

Paetyangkul *et al.*¹⁵⁶ evaluated the extent of OIIRR following 4, 8 and 12 weeks of light (25 g) and heavy (225 g) buccally directed forces on maxillary

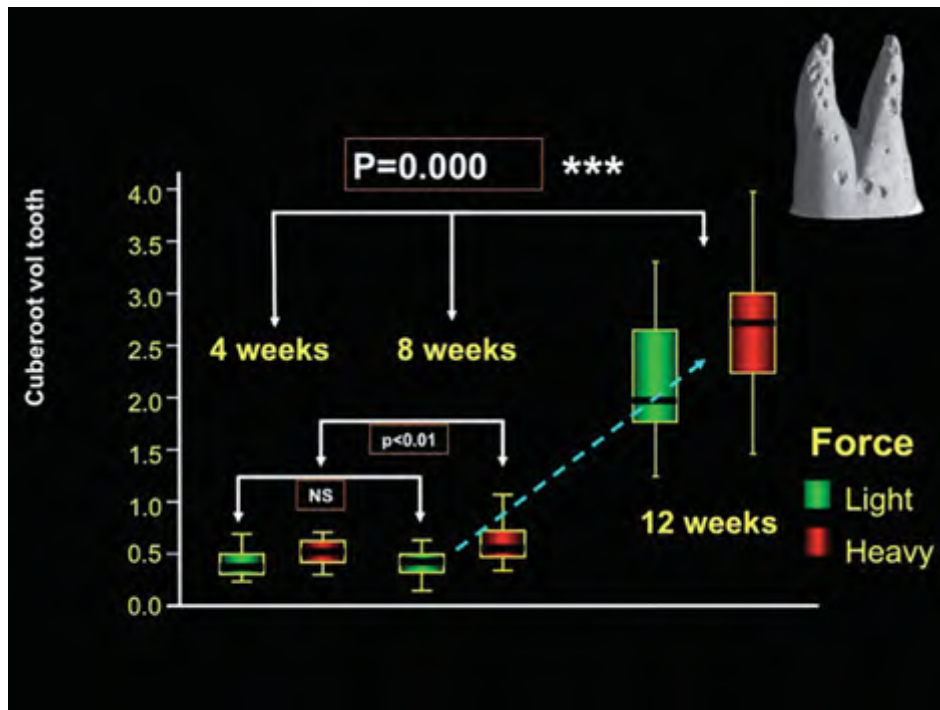


Fig. 7.7 Amount of root resorption following 4, 8 and 12 weeks of light (25 g) and heavy (225 g) buccally directed orthodontic force.

and mandibular first premolars and concluded that the amount of OIIRR increased significantly with treatment time (Fig. 7.7).

Distance of tooth movement

As previously discussed, teeth that were moved large distances had extended exposure to the resorptive process. Therefore, the severity of OIIRR may be regarded to be positively related to the distance of tooth movement^{127,153,157-159}. The upper incisors are commonly moved the greatest distance and are at the highest risk of OIIRR^{153,157,158,160,161}.

Magnitude of applied force

Many animal studies¹⁶²⁻¹⁶⁴ and human studies^{13,40,165-167} have agreed that the force magnitude was directly proportional to the severity of OIIRR. Heavy force induces excessive hyalinization and interferes with repair process of resorption craters^{6,27,38,41,163,168}. Recent SEM and micro-CT studies on human upper first premolars involved 25 g and 225 g of buccal force and intrusive force respectively found an increased amount of OIIRR with an increased force level^{14,16}.

Different appliances and treatment techniques

Numerous studies have compared the extent of root resorption following treatment of different types of orthodontic appliances. McNab *et al.*¹⁷¹ found more ERR in patients treated with Begg appliances than in those treated with edgewise appliance. The excessive lingualization of the maxillary incisor root by torquing force at the end of stage III of the Begg technique may explain the higher incidence of ERR. Blake *et al.*¹¹² compared radiographically the amount of apical root resorption after orthodontic treatment with edgewise and SPEED, the self-ligating appliance. There was no statistically significant difference in root resorption between the two appliance systems. Even though a recent radiographic study showed that the lower left central incisor was shorter at the end of treatment using the SPEED appliance when compared to the Tip-Edge and MBT straight wire technique, this seemed to be related to the proclination of the lower incisors and their image on the DPT¹⁷².

One radiographic study established that fixed appliances were more detrimental to the roots of upper incisors than removable appliances¹⁰⁴. Barbagallo *et al.*¹⁷⁴ compared the extent of root

resorption between conventional orthodontic appliances and clear plastic aligners and discovered that teeth subjected to light orthodontic force of 25 g displayed similar amounts of root resorption to those induced by the clear plastic sequential aligners.

The use of intermaxillary elastics increased the amount of OIIRR due to the existence of jiggling forces¹⁰⁴, however, another group of authors found no correlation¹⁵³.

Direction of force

The type and direction of tooth movement have a considerable role in OIIRR. It is expected that intrusion and torque have a higher force per unit area and thus cause more tissue necrosis and OIIRR⁷. Some authors suggested less root resorption associated with bodily movement compared with tipping due to the different stress distribution^{7,175}. It was found that intrusion of teeth caused about four times more root resorption than extrusion¹⁷⁶. Weekes and Wong¹⁷⁷ observed root resorption at the interproximal region of the cervical third part of the root after extrusion, indicating that orthodontic extrusion was not without risk. Harris *et al.*¹⁶ compared the amount of root resorption using light (25 g) and heavy (225 g) intrusive forces and found that the volume of root resorption craters was directly and significantly proportional to the magnitude of intrusion force used (Fig. 7.8). Costopoulos and Nanda¹⁷⁸ investigated the effect of intrusion on ERR of maxillary incisors and concluded that intrusion with low forces could be effective in reducing overbite while causing only a negligible amount of ERR.

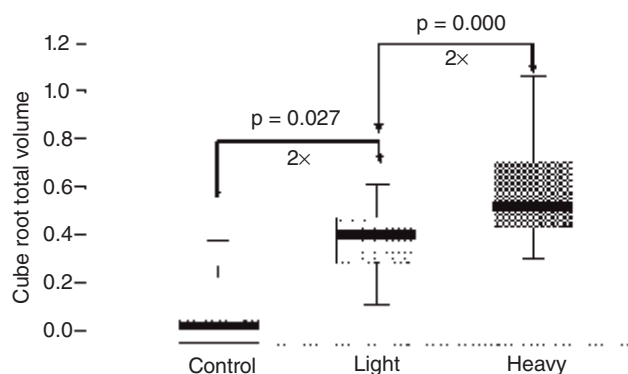


Fig. 7.8 Amount of root resorption following 4 weeks of intrusive light (25 g) and heavy (225 g) orthodontic force.

Duration of force application

There are conflicting reports as to whether continuous or discontinuous force produces a difference in the amount of OIIRR. The varying durations and frequencies of interruption in the applied forces may have led to varied results.

Levander *et al.*¹⁸⁰ radiographically evaluated the effect of a treatment pause of 2–3 months, on teeth in which EARR was discovered after an initial treatment period of 6 months with fixed appliances. The amount of root resorption was significantly less in patients treated with a pause than in those treated without interruption. The interruption of the forces facilitated reorganization of damaged periodontal tissue and reduced root shortening. Weiland¹⁸² compared the amount of root resorption when subjected to constant or dissipating forces. Constant force was induced by a superelastic wire for 12 weeks whereas dissipating forces were induced by stainless steel wire that was activated every 4 weeks. The results showed that the resorption craters on the teeth receiving constant force were 140% greater than on the teeth of the dissipating forces group. A micro-CT volumetric study by Ballard *et al.*¹⁸³ quantified the volume of root resorption crater following intermittent orthodontic forces (4 days per week) to be significantly lower than continuous orthodontic forces.

Extraction versus non-extraction treatment protocols

There are studies which have discussed the amount of OIIRR associated with extraction treatments^{114,153,171}. Extractions for severe crowding do not have as much impact on movement of the maxillary incisors as the displacement following extractions for overjet reduction.

REPAIR OF OIIRR

Repair of root resorption craters begins when the applied orthodontic force is discontinued or reduced below a certain level^{6,7}. According to Schwarz¹⁸⁵, when the orthodontic force reduced below the optimal force of 20–26 g/cm², root resorption stopped. Many studies have demonstrated that the resorptive defects were repaired by deposition

of new cementum and establishment of new PDL^{8,9,38,186–188}.

Brudvik and Rygh^{5,189} have shown that the OIIRR reparative process was similar to cementum formation during tooth development which started in the periphery of the resorption craters. Root resorption occurred even after active force was terminated. This could be explained by the slowness of clast cells to adapt to a change of stimuli¹⁹⁰, the persistence of necrotic tissue in the PDL-enhanced root resorption and the retention of the tooth in the new position prolonging passive stress in the PDL. Osteoclastic activity decreased when all necrotic tissue in the PDL has been resorbed. The multinucleated TRAP-positive staining cells concentrated between remnants of hyalinized tissue in the periodontal membrane and in root resorption craters. TRAP-negative mononucleated fibroblast-like cells were observed close to the newly formed cementum. As the reparative process progresses, there was a reduction in the number of TRAP-positive cells on the root surface and in the periodontal membrane. New PDL cells, fibres and blood vessels were observed where the hyalinized tissue had been completely removed.

There are two types of repair: anatomical and functional²⁹. Anatomical repair is characterized by the restoration of the root surface to its original contour and a functional repair occurs when the exposed dentin has been covered by a thin layer of repair cementum, resulting in a deficient root outline. In both types, the PDL is restored to its original width.

Vardimon *et al.*¹⁹¹ described the phases of root resorption repair. The incipient phase (14 days) was a transitional stage from no apposition (lag phase) to active deposit stages of repair cementum. The extent of the lag phase can be explained by the dissipation of residual forces¹⁹² and the replacement of clastic cell population by a blastic cell line^{27,38}. The lag phase was followed by a peak phase (14–28 days) which was a spurt in matrix formation. The peak phase was characterized by an initial incorporation of extrinsic fibres into the intrinsic cementum matrix which suggested a development towards functional repair. Then, a steady deposit phase (42–56 days) of mixed fibrillar cementum followed, which was interrupted by the removal of the retention appliance.

The amount of root resorption repair increases with time^{8–10,169}. Owman-Moll and Kurol¹⁹³ demon-

strated more reparative cementum in the resorption cavities after 6 and 7 weeks of retention when compared to 2 and 3 weeks of retention. The reparative process increased during the first 4 weeks of retention and, after 5–6 weeks, the process slowed down and reached a steady phase¹⁰. The reparative process seemed to continue for a long period of time.

Different spatial patterns of repair have been described, starting either from the periphery of the resorption cavity^{5,13,189,194} and or from the centre of the resorption crater outward⁸. The difference in findings could be due to the direction of histological sectioning.

A recent micro-CT study has shown that root resorption continued for another 4 weeks after orthodontic force was ceased¹⁹⁵. The reparative processes seemed to be different for different levels of force application. The reparative process reached a steady rate after 4 weeks of passive retention following the application of 4 weeks of light force whereas the majority of the reparative process occurred after 4 weeks of passive retention following the application of 4 weeks of heavy orthodontic force (Fig. 7.9).

ORTHODONTIC RELAPSE AND OIIRR

Following the active appliance removal, there is a conversion of the former pressure side of the active treatment period into the tension side during the relapse period¹⁹¹. Langford and Sims⁹ showed that relapse forces were capable of causing significant root resorption for up to 3 months after RME. Zimring and Issacson¹⁹⁶ found that residual loads acting on the expansion appliance dissipated within 5–7 weeks during retention. In addition, the teeth were held in an overcorrected position following expansion which resulted in an abnormal occlusal relationship. The occlusal force may be sufficient to perpetuate a small amount of ongoing resorption.

CLINICAL CONSEQUENCES OF OIIRR

A long-term radiographic evaluation of root resorption after active orthodontic therapy revealed progressive remodeling of the root surface¹³⁹. The jagged resorbed edges were smoothed and sharply pointed root ends became round with time. However, the

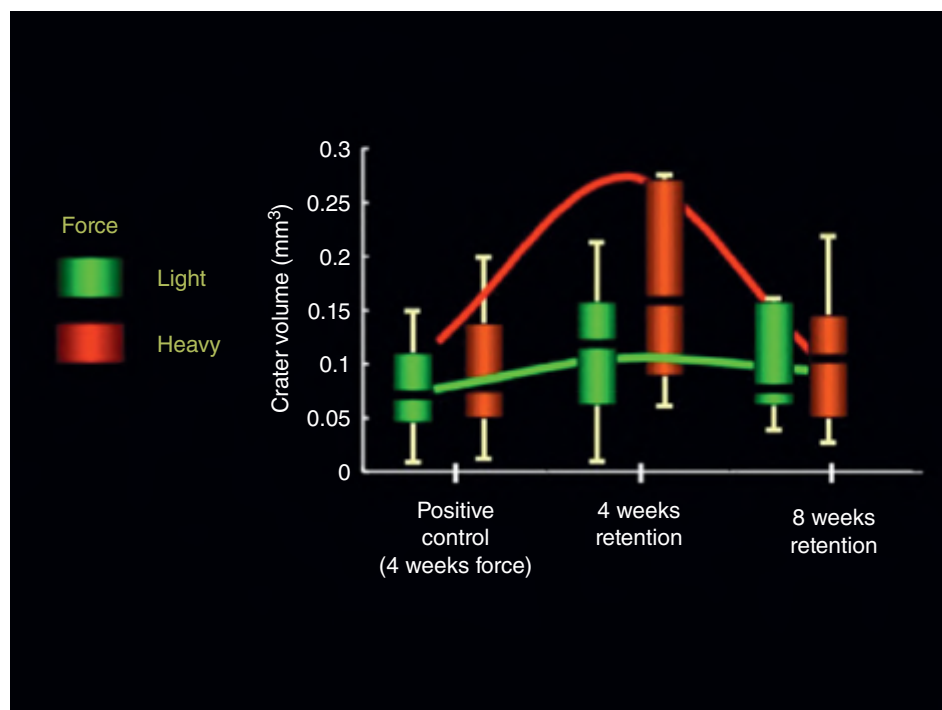


Fig. 7.9 Amount of root resorption crater following 4 and 8 weeks of repair after the application of light (25 g) and heavy (225 g) orthodontic forces for 4 weeks.

original root contours and lengths were never re-established. Severely resorbed teeth were found to be functioning in a reasonable manner. Out of the 100 subjects that were studied, the worst outcome was hypermobility, which was only observed in two patients¹³⁹.

A reduction in root length due to apical resorption has been described as less detrimental than an equivalent loss of periodontal attachment at the alveolar crest especially in cases ≤ 3 mm of ERR²². Kalkwarf *et al.*¹⁹⁷, with the aid of a computer graphics system, showed a nearly linear relationship between root length and percentage of periodontal attachment. Results indicated that 4 mm of root resorption translated into 20% of total attachment loss and 3 mm apical root loss equals only 1 mm crestal bone loss. After the initial 2 mm apical root loss, calculations revealed every additional 2 mm root loss equaled to only 1 mm of crestal bone loss. Therefore, patients who were susceptible to marginal periodontal breakdown may have a higher risk of losing severely resorbed teeth prematurely. This emphasizes the importance of periodontal disease control in patients with severely resorbed teeth. In addition, teeth with abnormally short roots and loss of periodontal attachment may not be suitable as future bridge abutments.

PREVENTION AND MANAGEMENT OF OIIRR

Clinically, several approaches have been suggested in the literature to minimize OIIRR and were summarized by Vlaskalic *et al.*¹⁵⁴ and Ghafari¹²⁸. The recommendations include decreased treatment duration^{27,144}, the use of light intermittent forces^{6,27,38,41}, avoidance of sustained jiggling intermaxillary elastics⁹⁹, limiting tooth movement for OIIRR-prone teeth, e.g. intrusion and torque¹¹³, habit control¹¹⁵ and a thorough assessment of familial tendency and medical history^{23,64,114,198}.

Vlaskalic *et al.*¹⁵⁴ also suggested that the treatment of moderate to severe malocclusions be commenced when most of the incisors had open apices, which is before the age of 9 years. They recommended this strategy as incomplete root formation has been found to be significantly associated with a lower severity of OIIRR^{102–104}.

It was strongly suggested that periapical radiographs should be taken at least every year to determine the presence of root resorption¹²⁸. Minor resorption or an irregular contour of the root that were seen 6–9 months after the last radiograph indicated an increased risk of further root resorption¹⁴⁴. The original treatment goals must be reassessed depending on the extent of root resorption detected

or the force levels should be modified or a 2–3 months' pause in treatment with passive archwires should be implemented¹⁸⁰. Additional radiographs should be taken every 3 months in at-risk patients to monitor the progress of root resorption^{11,128}. It is mandatory to take final radiographs at the time of removal of fixed appliances³⁴. In the case of teeth with severe OIIRR, follow-up radiographs are recommended until additional root loss is no longer detected¹⁹⁹.

Numerous animal studies have been conducted to investigate the possibility of reducing the risk of OIIRR by applying drugs that modulate the activity of osteoblasts, osteoclasts and odontoclasts. Arginine–glycine–aspartic acid containing peptides inhibit the resorptive activity of isolated clast cells by targeting the intergrin receptor expressed by odontoclasts and have been shown to be effective in reducing root resorption during tooth movement²⁰⁰. Low dose systemic administration of doxycycline in rats may have an inhibitory effect on OIIRR via reduction of odontoclasts, osteoclasts, mononuclear cells and TRAP-positive cells on the root²⁰¹. Low doses of thyroid hormone also played a protective role on the root surface against OIIRR²⁰². Steroid-treated rats also displayed significantly less root resorption on the compression side and fewer TRAP-positive cells within the PDL space on the same side⁷⁸. However, many of these drugs also altered the activity osteoblasts and osteoclasts in alveolar bone which may interfere with the rate of tooth movement. On the other hand, PGE₂ enhanced orthodontic tooth movement but increased the amount of root resorption^{3,203}.

In an animal study Foo *et al.*¹⁵ evaluated the effect of systemic fluoride intake on orthodontic root resorption and found that fluoride on average reduced the size of resorption craters. Even though there was a trend in reducing the volumetric amount of root resorption the effect was variable and found not to be statistically significant (Fig. 7.10).

Recent research has focused on identifying biological markers in the gingival crevicular fluid (GCF) in the light of relating these markers and the risk of OIIRR. If successful, this technique could be easily implemented in identifying the patients at risk of OIIRR prior to orthodontic treatment and treatment planning could be modified accordingly. Mah and Prasad²⁰⁴ showed elevated levels of dentine phosphoproteins in the GCF in resorbing primary teeth

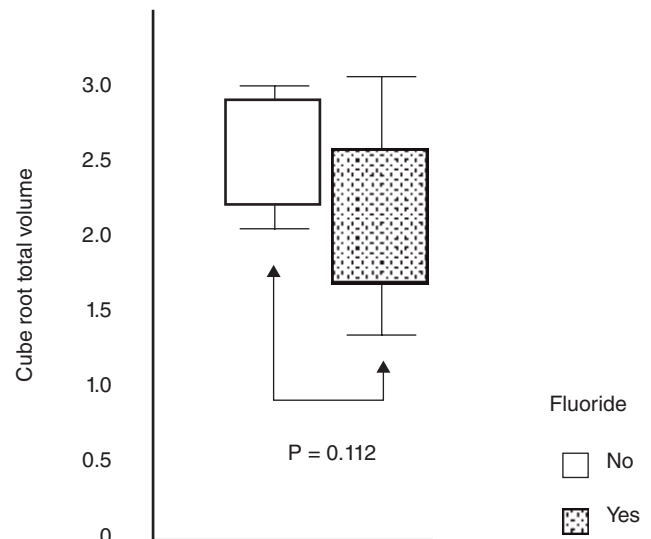


Fig. 7.10 The effect of systemic fluoride on the amount of orthodontically induced root resorption in rat.

and active orthodontic treated teeth compared to untreated permanent teeth. In addition, Balducci *et al.*²⁰⁵ identified an increase in dentin phosphophoryn and dentin sialoprotein concentration in the GCF of the severe root resorption group. Therefore, dentin phosphophoryn and dentin sialoprotein could be suitable biological markers for identifying at-risk patients and monitoring root resorption during orthodontic treatment.

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8

Root Resorption with Self-Ligating Brackets

Maria Mavragani, Nikolaos Pandis and Theodore Eliades

INTRODUCTION

Although self-ligating brackets have existed for a long time in orthodontics and have been extensively advertised by manufacturing companies during recent years, considerably less extensive relative scientific evidence has been published in orthodontic literature. In regard to root resorption after treatment with self-ligating bracket systems there is a severe lack of research information.

Orthodontists have tried to eliminate orthodontically induced inflammatory root resorption (OIIRR)¹ by evaluating several treatment-related factors. Duration of treatment, extraction/non-extraction treatment approach, use of intermaxillary elastics, rectangular archwires, type of appliances, treatment techniques, type and extent of tooth movement, type and magnitude of force, have been examined².

RELEVANT LITERATURE

In the field of self-ligating appliances, Blake *et al.*³ compared the severity of OIIRR between SPEED and edgewise appliances. SPEED (Strite Industries Ltd, Ontario, Canada) are active self-ligating brackets, which provide a continuous rotatory and torque action through a spring clip mechanism. The effect of this continuous action on root integrity against the interrupted action of the edgewise system was studied using periapical radiographs. No statistically significant difference between the two appliances considering OIIRR was found for the maxillary central and lateral incisors and the mandibular central incisors. The difference was significant for the mandibular lateral incisors ($p < 0.05$) (Fig. 8.1).

The authors commented that ‘although the spring clip mechanism in the SPEED bracket delivers a constant force, this force is not of sufficient magnitude to increase the root resorption observed after orthodontic treatment’.

In a very recent study, Pandis *et al.*⁴ investigated the amount of OIIRR after treatment with passive self-ligating and conventional brackets, both with a 0.022" slot. Orthodontic treatment was performed with Damon2 (ORMCO, Glendora, CA, USA) and Microarch (GAC, Bohemia, NY, USA) self-ligating appliances respectively. Pre- and post-treatment panoramic radiographs, including a graded tip of a periodontal probe for magnification assessment, were used. Despite a trend for more severe OIIRR for patients treated with the passive self-ligation appliance ($p = 0.06$), overall no statistically significant difference was found concerning the severity of OIIRR between passive self-ligating and conventional edgewise appliances.

Apart from the above presented two clinical studies, no other relative scientific report exists in orthodontic literature. However, manufacturers claim that self-ligating appliances reduce root resorption without support of solid scientific evidence. The lack of this kind of study may be due to the late introduction of self-ligating appliances in orthodontic clinics of educational institutions, where such investigations are usually conducted.

POTENTIAL FACTORS AFFECTING OIIRR

In light of the lack of scientific evidence on the matter, an evaluation of factors related to the treatment with self-ligating appliances will be attempted,

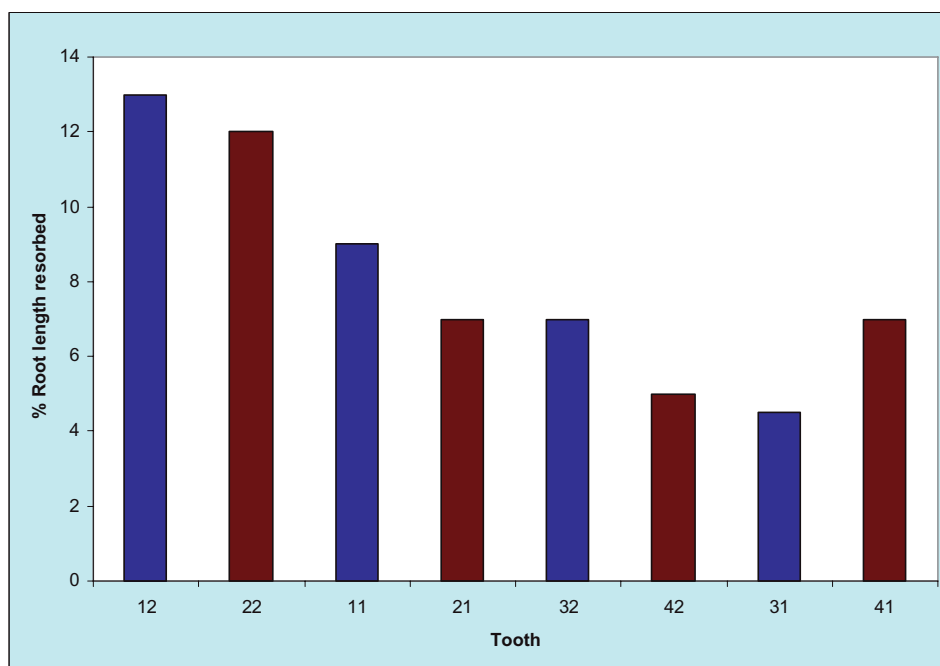


Fig. 8.1 Prevalence of root resorption in edgewise (blue) versus SPEED (red) appliances. (Adapted from Blake *et al.*, 1995³, with permission from Elsevier)

based on our current knowledge on their importance considering OIIRR. This is by no means any attempt to answer the *million dollar question*: ‘Do self-ligating appliances cause more, less or similar OIIRR than conventional appliances?’ It is only the attempt of a researcher–clinician to synthesize knowledge, making some points for future research.

Magnitude of force

One of the advocated benefits of self-ligating appliances has been the possibility to use lighter forces during treatment due to lower friction⁵. Force magnitude has been considered as a risk factor for OIIRR^{6,7}. However, more recent findings indicate that the magnitude of orthodontic force up to 200 cN does not necessarily increase the severity of root resorption. The increase of force used to move premolars buccally in humans, from 50 cN to 100 and 200 cN did not affect the amount of root resorption^{8,9}. Similar results were obtained by Maltha *et al.*¹⁰, when controlled orthodontic forces of 10, 25, 50, 100 and 200 cN were applied to premolars in beagle dogs. In another study, the extent of hyalinized zone did not seem to be related to the force level¹¹. According to previous reports, the possibility for lighter forces during treatment with self-ligating

appliances would not be of any advantage for the reduction of OIIRR, given that forces used in any treatment should not exceed the level of 200 cN.

Reduced treatment time

There seems to be an agreement on the duration of active treatment as a risk factor for OIIRR. Most studies agree that *the longer the treatment, the shorter the roots*^{10–14}. Self-ligating appliances have been shown to reduce treatment time by 4–6 months and four to seven visits^{15,16}. However, some recent prospective studies failed to show any reduction of time required for initial tooth alignment^{17,18}, correction of mandibular crowding¹⁹, or en masse space closure with sliding mechanics, when self-ligating appliances were used²⁰. According to the author of the last paper, ‘any treatment time savings might still be possible during the latter stages of treatment, or only in certain types of patients, or there might be no time saving’. With the present knowledge on OIIRR’s risk factors, in regards to ‘time saving’ one would expect *root substance saving*. In assessing the effect, the actual decrease in treatment duration should be considered; however, in most cases the time saving is not of the order to justify potential effects on OIRR.

Higher frequency of non-extraction treatments

It has been claimed that some self-ligating appliances increase the possibilities of treating more cases without extractions of dental units and maintaining complete dentitions. The effect of extractions on OIIRR has been evaluated in several studies. With some exceptions^{3,22}, most studies agree that there is no relation between extractions and severity of OIIRR^{12,23,24}. If that is the case, any facilitation of non-extraction treatments by self-ligating appliances would not influence the integrity of roots.

Continuous forces

One of the main advantages of self-ligating appliances has been the possibility of application of continuous forces, which is considered beneficial for tooth movement from a biomechanical point of view. Nevertheless, considering OIIRR, several reports conclude that continuous forces cause more severe root resorption than dissipating forces. In a study by Maltha *et al.*¹⁰ in beagle dogs, an inactivation of appliances for 8 hours per day resulted in 40–70% less root resorption than continuous forces (Fig. 8.2). Similar results were obtained in rats by daily inactivation for 4–9 hours²⁵ (Fig. 8.3).

A clinical experimental study by Owman-Moll *et al.*²⁶, where the first maxillary premolars were moved buccally by means of a fixed orthodontic appliance, did not reveal any difference in the amount or severity of OIIRR between continuous and interrupted (for 1 week every 4 weeks) forces of the same magnitude (50 cN). In another study by Acar *et al.*²⁷ continuous use of elastics for tipping of maxillary first premolars produced significantly more root resorption than discontinuous (for 12 hours per day) use of elastic bands. Those results were confirmed by Weiland²⁸. A total of 84 premolars scheduled for extraction from 27 individuals were moved buccally, in a split mouth experimental design study. One premolar was loaded using a 0.016" stainless steel wire, which was reactivated every 4 weeks, since the applied force was rapidly declining to zero after activations. A superelastic wire was used on the premolar of the contralateral side and was left untouched after the initial activation. After 12 weeks of experiment, teeth were extracted and root resorption lacunae were evaluated. Except for the depth of resorption lacunae, their perimeter, area, and volume were 140% greater for the teeth in the 'superelastic' than in the 'steel' group.

In clinical conditions, 2–3 months' temporary halt in treatment after the initial 6 months with fixed appliances was shown to cause a significant reduction at the amount of root resorption, as demonstrated in standardized radiographs²⁹ (Fig. 8.4).

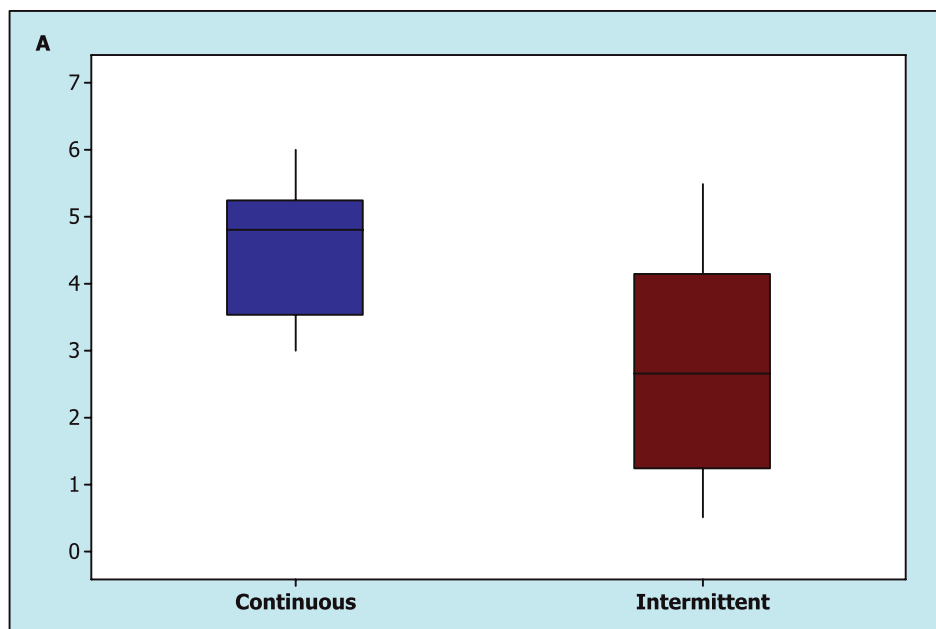


Fig. 8.2 Box and whisker plots of the results of the measurements for continuous and intermittent force regimes, indicating the medians, and the 5th, 25th, 75th and 95th percentiles.

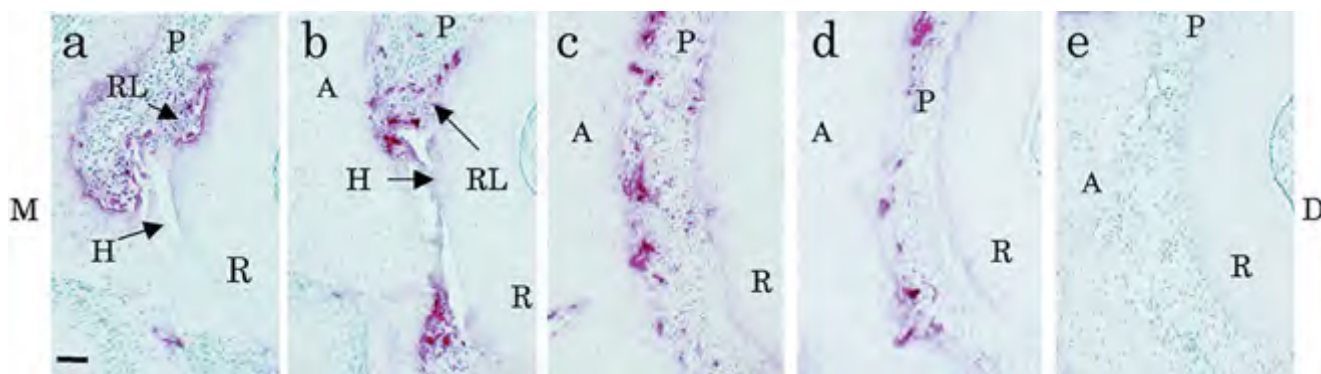


Fig. 8.3 Mesial compression sides of distobuccal roots of first molar in five groups on day 14. Hours given indicate the time of inactivation of the appliances per day. (a) 0-hour group; (b) 1-hour group; (c) 4-hour group; (d) 9-hour group; (e) control group. A hyalinized tissue and undermining bone resorption were found in the 0- and 1-hour groups (a,b). In contrast, little hyalinized tissue and undermining bone resorption were found in the 4- and 9-hour group (c,d). In the control group, TRAP-positive cells could not be recognized on the root surface (e). (A, alveolar bone; R, root; P, periodontal ligament; RL, resorption lacuna; H, hyalinized tissue; M, mesial; D, distal. TRAP stain. Bar = 50 μ m) (Fig. 8.3 appears as fig. 8 in Kameyama *et al.*, 2003²⁵)

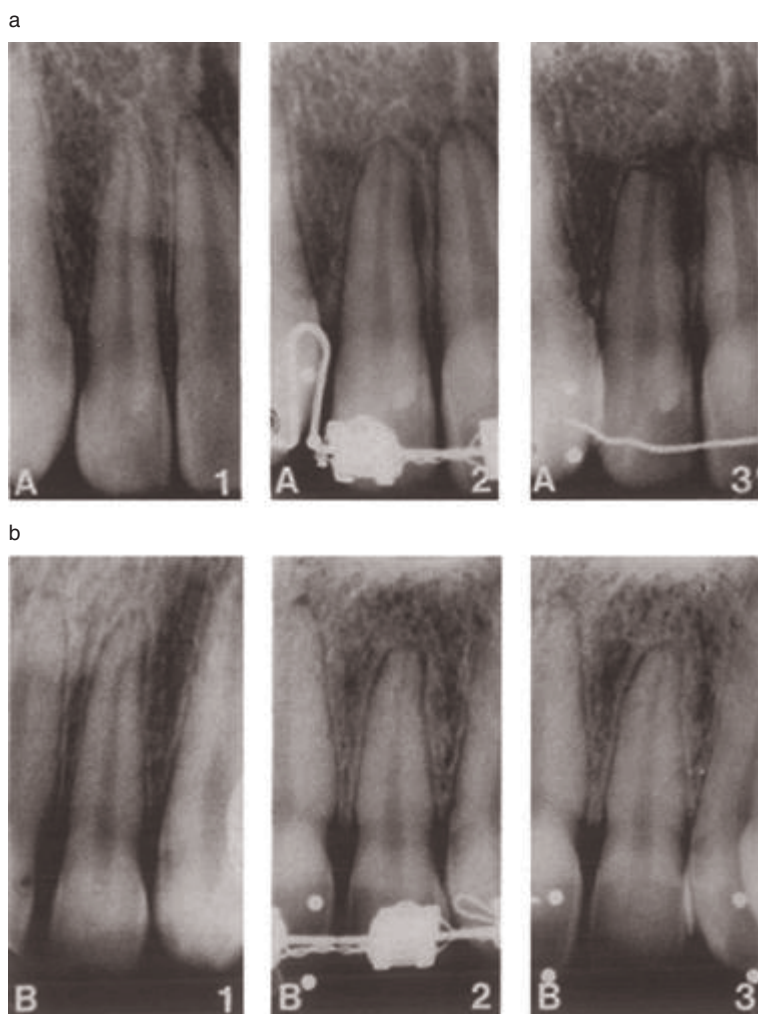


Fig. 8.4 Typical effect of root resorption. (a) Treatment without pause, (b) Treatment with pause. (1) before treatment, (2) 3 months after treatment initiation, and (3) after treatment. (Adapted from Levander *et al.*, 1994²⁹, with permission from Oxford University Press)

The rationale behind the studies showing increase of OIIRR by continuous forces, lies in the importance of rest periods for the repair of resorption defects on roots. As Rygh³⁰ has stated, 'by continued orthodontic force application the resorption process will proceed even after all hyalinized tissue is eliminated. If the orthodontic force is discontinued or falls under a certain level, the resorption lacunae are repaired.' The authors found that following force application for mesialization of Wistar rat molars, 21 days after the force was terminated, repair of resorption lacunae could be seen in all animals (Fig. 8.5). However, some resorptive activity was still apparent in the proximity of the remaining hyalinized tissue (Fig. 8.6). No tartrate-resistant acid

phosphatase (TRAP)-positive cells could be observed on the root surface (Fig. 8.7). By using transmission electron microscopy, Brudvik and Rygh³¹ demonstrated that after force termination, the repair process was similar to the early cementogenesis occurring during tooth development (Fig. 8.8). Furthermore, decrease in mechanical stress and hyalinized tissue, recovery of form and function of blood vessels, reduction of cytokine production and subsequent odontoclast formation have been proposed as protective mechanisms offered by dissipating forces²⁵. Based on results obtained by studying cementum and periodontal ligament after continuous intrusion in humans, Faltin *et al.*³² suggested that the ideal level of continuous forces should be lower than that

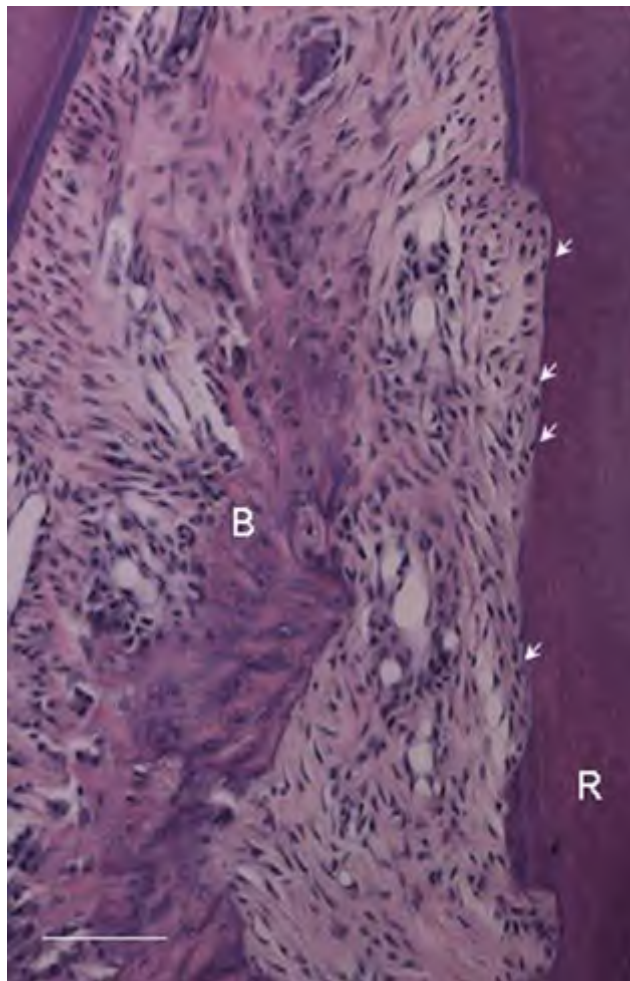


Fig. 8.5 Transition to repair (day 21) with mononucleated cells on root surface (arrows). (R, root; B, alveolar bone; bar = 100 μ m)

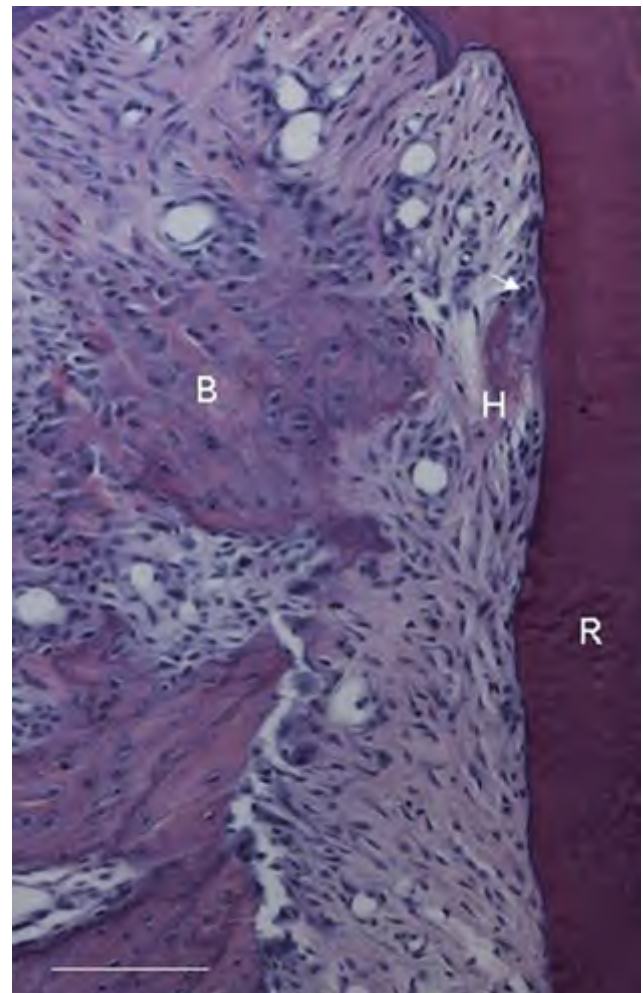


Fig. 8.6 Day 21. Repair of an earlier resorption lacuna. Multinucleated cells (arrow) close to remaining hyalinized tissue (H). (R, root; B, alveolar bone; bar = 100 μ m)

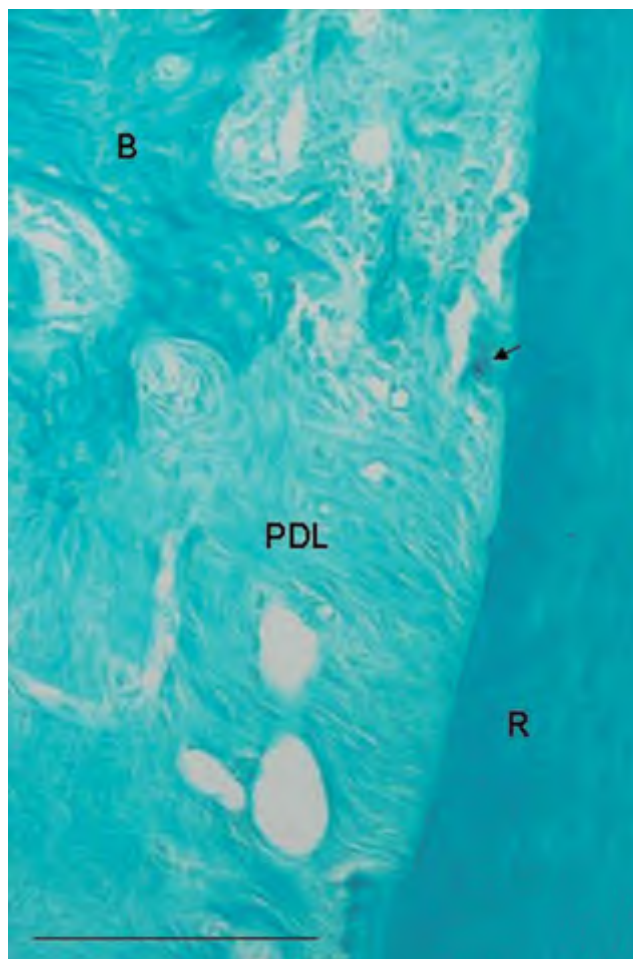


Fig. 8.7 Day 21. Absence of TRAP-positive cells on root. Weakly stained TRAP cell in remnants of necrotic tissue in periodontal ligament (PDL). (R, root; B, alveolar bone; bar = 100 μ m)

of the intermittent forces, in order to preserve the integrity of the tissues.

Weiland³³ concluded that ‘forces that are heavy enough to lead to necrosis of the periodontal ligament and last long enough to prevent the root from recovering from damage to the surface seem to be dangerous and cannot be recommended’. In clinical orthodontics most forces are continuous, but decline between activations. The duration of this treatment pause has not been specified in the literature but it is estimated to be 1 or 2 weeks¹⁰.

Self-ligating appliances are said to produce continuous orthodontic forces. Since the benefit of treatment breaks presented above will not occur, in the light of the present knowledge, root integrity with self-ligating brackets relies on their capacity to elimi-



Fig. 8.8 Repair of resorptive defect after force cessation 21 days after tooth movement. Light zone (arrows) separates a layer of new electron dense material (asterisks) from the resorbed dentine (D). Layer of collagen fibrils (f) between the dense zone and the PDL cells (N). (ER, endoplasmic reticulum; bar = 2 μ m) (Adapted from Brudvik and Rygh, 1995³¹, with permission from Oxford University Press)

nate the initiation of the resorption process. This was speculated to be the case, due to the possibility for light force self-ligating appliances to preserve the integrity of blood vessels, preventing the formation of necrotic tissue²¹. This would be of extreme importance for the orthodontic community in our effort for *biologically friendly tooth movement*, but it has to be proven on a histological level, in further studies.

However, we should not consider root resorptive process as a characteristic of orthodontic treatment alone. External root resorption has also been observed on untreated teeth^{7,34} (Fig. 8.9). Resorptive activity might already be present before we bond our

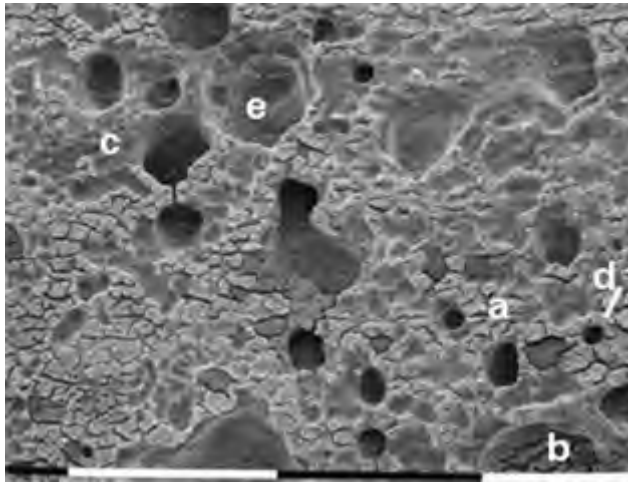


Fig. 8.9 Surface of untreated root exhibiting intact cementum (a), repaired earlier resorption (b), superficial resorption (c), small-isolated lacuna (d), and deep resorption with open dentinal tubuli (e). (Day 0 SEM; bar = 100 μ m) (Adapted from Mavragani *et al.*, 1994³⁴, with permission from Oxford University Press)

patient with what we think to be ‘the best and more advanced appliance’. In that case, we cannot feel protected against OIIRR, by an appliance that does not initiate formation of lacunae. The causes and mechanisms of root resorption are multifactorial and orthodontic treatment is only one part of the picture. Patient-related factors, among them genetic predisposition, are very important and difficult to control.

Despite the complexity of the problem, it is our responsibility to clarify the effect of our appliances on oral tissues, perform biologically predictable treatments and provide the scientific community with sound evidence considering our treatment modalities. Self-ligating appliances have been considered as one of the three important areas for the future of orthodontics, together with three-dimensional imaging and endosseous anchorage³⁵. This field deserves our special consideration, while planning future research.

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9

Attachment of Oral Microbiota to Dental Surfaces

Daniel J. Smith

INTRODUCTION

Dental plaque is the most well studied and, perhaps, the most complex of biofilms in the human body. In fact the oral cavity contains not just one, but several distinct biofilms, each of which has specific habitats and niches. The teeth, the buccal, gingival and palatal epithelia, crevicular epithelia, the tongue and the broad ducts of minor salivary glands each have features which provide for biofilms that are characteristic of those environments. Even on the tooth surface, biofilm compositions differ with respect to location within the mouth, the type of surface and super- or subgingival location. Habitats on tooth surfaces can be modulated by many conditions such as temperature, host- or bacterial-derived nutrients, pH, oxygen tension, oral hygiene, innate and adaptive host defenses and external sources of microbial challenge. In addition, dental biofilms are not static but change as biofilm communities modulate between conditions of health and disease.

Oral biofilms incorporate all the features of general biofilm development. Marsh¹ has described several stages in the establishment of a biofilm community. The first stage is transmission of bacteria from a source external to the host's biofilm via the planktonic or bulk fluid phase which overlies the surface to be colonized. For example, maternal microbiota can be transmitted via saliva to the infant by kissing or food tasting. Water or food can also serve as vehicles of bacterial transmission. Besides being a vehicle for bacterial transmission and relocation, the bulk fluid also provides nutrients and removes waste products from the developing biofilm.

The second phase of biofilm community development is the initial attachment and colonization of transmitted organisms. At the earliest stage, weak electrostatic forces provide reversible attachment to the acquired pellicle coating either the enamel or earlier colonizing bacteria. Irreversible attachment can then follow via bacterial adhesins which bind to receptors within the dental pellicle or on colonized bacteria. In the oral cavity streptococcal species comprise these 'pioneer microorganisms'. These then multiply, coaggregate and detach to be cleared or populate new sites.

The biofilm is then modified by environmental conditions created by the pioneer species. Changes in pH, nutrient addition or removal and host anti-bacterial factors in the bulk fluid can interfere with bacterial attachment of some organisms or promote colonization of others via epitopes exposed through proteolytic cleavage of host or bacterial components. These changes usually allow colonization of additional bacterial species whose attachment or growth is enhanced by further modifications in the biofilm environment, creating yet more complexity. This so-called microbial succession increases the species diversity until the biofilm matures into a climax community which, on the tooth surface, is comprised of many niches of bacterial function. This biofilm is much more stable than less developed communities because of the multiple levels of adaptation generating it. Socransky and Haffajee² have defined the climax community as 'a self-replicating entity that reproduces itself with remarkable fidelity'. However, the climax community can undergo significant change, especially evident with a persistent change in external conditions or when the host becomes compromised.

Bacterial interactions contributing to biofilm development

Many interactions and interdependencies participate in the development of microbial communities in the oral cavity³. Host–bacterial interactions and inter- and intrabacterial communication and attachment networks contribute to the formation of a climax community. Essentially all interactions of bacteria with the teeth take place not on dental surfaces themselves, but with components contained within the salivary pellicle which forms shortly after enamel surfaces are exposed to saliva. These components, many of which are discussed below, can bind to bacterial products on the cell surfaces or in the biofilm matrix. For example, oral streptococci, including cariogenic *Streptococcus mutans*, have adhesins which have specificities for salivary agglutinin. The fact that most salivary proteins can bind a variety of oral streptococcal species may account for the observation that many of these organisms are among the earliest colonizers in infancy and of cleaned tooth surfaces. Another prominent member of the mature oral biofilm is *Actinomyces naeslundii* whose fimbria can bind epitopes on pellicle-bound proline-rich proteins of salivary origin. *Porphyromonas gingivalis*, a subgingival Gram-negative bacterial species associated with periodontal disease, has been reported to interact with fibrinogen.

Interbacterial attachment phenomena are highly diverse. These attachment phenomena provide a means for bacteria to join the maturing biofilm and provide an environment for exchange of bacterial material (e.g. DNA, metabolic end-products) for adaption or growth of current ‘residents’. These interactions can lead to microstructures within the plaque. For example, species of oral streptococci decorate the surface of *Fusobacterium nucleatum*, an elongated Gram-negative anaerobic bacterium. This results in what has been described as a ‘corn cob’ appearance. Kolenbrander *et al.*⁴ have made extensive studies of these coaggregation phenomena. They have shown that coaggregation among common oral biofilm inhabitants is quite specific, resulting in species-specific ‘coaggregation profiles’. Some biofilm inhabitants such as *P. gingivalis* manifest few cross-species interactions, while *F. nucleatum* is reported to show the broadest number of interactions among speciated oral bacteria. They have also shown that *Streptococcus oralis* can act as a bridging

organism for *F. nucleatum* and *Prevotella loescheii*, two unrelated biofilm inhabitants. Differences in binding affinity by unrelated bacteria competing for the same structure on coaggregating organisms can also influence the ultimate composition of climax community.

Nutritional interdependence is also important in bacterial survival in the biofilm. For example, lactate is produced by carbohydrate metabolism by many oral streptococci including cariogenic *Streptococcus mutans*. *Veillonella* species can use this lactate for their metabolism and it has been suggested that this process can reduce the cariogenic potential of an acidogenic flora. Another example of this phenomenon is the observation⁵ that formate-requiring *Camphylobacter rectis* can use this metabolic product of *Streptococcus sanguis* carbohydrate metabolism for their own growth.

Other mechanisms are also important to the survival and growth of bacteria in the maturing biofilm on the tooth surface⁶. The density of bacterial cells in dental biofilms apparently results in a significant amount of horizontal gene transfer which can confer properties important for sustained growth. Such quorum-sensing mechanisms have been shown to be critical to biofilm formation of oral bacteria such as *Streptococcus gordonii* and *S. mutans*. The ability, or competence, of these bacteria to undergo genetic transformation, has been linked to their secretion of competence-stimulating peptides which initiate transcription of a gene pool involved with transformation and with acid tolerance. Increasing cell density activates this intrabacterial *comCDE* system. In contrast, the *luxS* quorum-sensing system of *S. mutans* affects biofilm formation among different species. Several other two-component regulatory systems have also been shown to be important in biofilm formation. These quorum-sensing systems can result in shared genes among phylogenetically distant bacteria in the same habitat.

THE ORAL BACTERIAL CHALLENGE

Modern techniques have identified over 650 different bacterial species in human dental biofilms⁷. Approximately half of these bacteria cannot yet be cultivated; thus their role in biofilm stabilization or pathogenesis is unknown. The diversity in bacterial composition is truly amazing in that nearly all bacte-

rial phyla are represented. In one study of orally healthy subjects using genetic amplification and sequencing techniques, up to 72 distinct species were shown to predominate in a single mouth⁸. The many habitats (e.g. supra- and subgingival tooth surfaces, tongue, buccal epithelium, hard and soft palates and tonsils) of the oral cavity were often colonized both with common species, e.g. *Streptococcus mitis* and *Gemella adiacens*, as well as with species unique to each site. Significant subject-specific diversity also exists, even among the predominating bacterial species of the oral cavity. The presence of disease creates another level of diversity since bacterial profiles in the mouth and especially on the teeth of healthy individuals differ from those profiles of subjects with disease.

The creation of these complex biofilms begins very early in life. Soon after birth the infant's oral cavity is colonized with *S. mitis* and *Streptococcus oralis* (on the oral epithelium) and *Streptococcus salivarius* (on the tongue)^{9,10}. These so-called pioneer organisms are vertically transmitted from the mother and are usually the principal oral streptococci in predentate infants. *A. naeslundii* also initiates colonization during this period. Modern DNA-based techniques for bacterial identification have revealed additional oral flora in the oral cavity during this early period of life, although, in some instances, colonization may be transient.

The eruption of teeth provides new habitats. Consequently the number and complexity of bacterial species in oral biofilms increases in this changing environment. Under normal dietary conditions, low levels of streptococci such as *Streptococcus sanguinus*, *Streptococcus gordonii* and *Streptococcus mutans* colonize during the first few years, although the degree of maternal infection and extent of exposure to dietary sucrose can influence the prevalence and colonization levels of the mutans streptococcal group. Other *Actinomyces* species also are detected after teeth erupt. Many Gram-negative, anaerobic microorganisms (e.g. *P. melaninogenica*, *F. nucleatum*, *Veillonella parvula* and *Selenomonas* species) can be observed in the mouths of children under 2 years of age¹¹, including bacteria associated with periodontal disease (e.g. *P. gingivalis*, *Tannerella forsythus* and *Aggregatibacter actinomycetemcomitans*). However, the detection frequency of the periodontal pathogens is lower than that of anaerobes associated with health (e.g. *Prevotella* and *Campy-*

lobacter species). Again, colonization of some of these anaerobes may be transient until later in life. Tanner¹¹ has suggested that tongue biofilms may serve as reservoirs for maturing dental biofilms.

Biofilm communities on supragingival surfaces follow a predictable pattern of progression, based on studies of recolonization of cleaned tooth surfaces of adults¹². Gram-positive species dominate the initial recolonization communities. Streptococcal species colonize and dominate biofilms formed on teeth during the first 24–48 hours, after which their percentages plateau or decline. *Actinomyces* species also appear during the early phase of biofilm formation, then numerically increase, and remain at higher percentages than the streptococcal species in established subgingival plaque. By 7 days, significant increases in Gram-negative bacterial percentages occur. *Fusobacterium*, *Veillonella* and *Capnocytophaga* species are prominent at this time and remain important members of the healthy supragingival climax community.

Changes in the amount and type of external nutrients can modulate the composition of the supragingival biofilm from one of health to one of disease. For example, the availability of sucrose will cause a shift in the populations of some saccharolytic microbiota, particularly the mutans streptococcal group (Fig. 9.1). These cariogenic streptococci initially bind to salivary components in the biofilm via one of the antigen I/II family of adhesins. This colonization is of little consequence to the host unless sucrose is present in the bulk fluid. In this event, glucosyltransferases, released by these streptococci, synthesize several types of glucans from this disaccharide. Glucans then aggregate mutans streptococci, thus increasing the percentage of this acidogenic bacterium in the biofilm. This process can change the habitat in several ways. The decrease in biofilm pH resulting from metabolically generated lactic acid puts the tooth structure at risk of demineralization. Such loss of tooth structure would create a new habitat. Also, certain bacteria, such as *Veillonella*, that favor acid environments can increase in numbers. Furthermore, glucan-dominated biofilm matrices can alter nutrient and metabolic end-product diffusion pathways within the biofilm.

Subgingival biofilms form on two different surfaces, the tooth and the gingival sulcus epithelium. In these locations, microflora colonize and draw

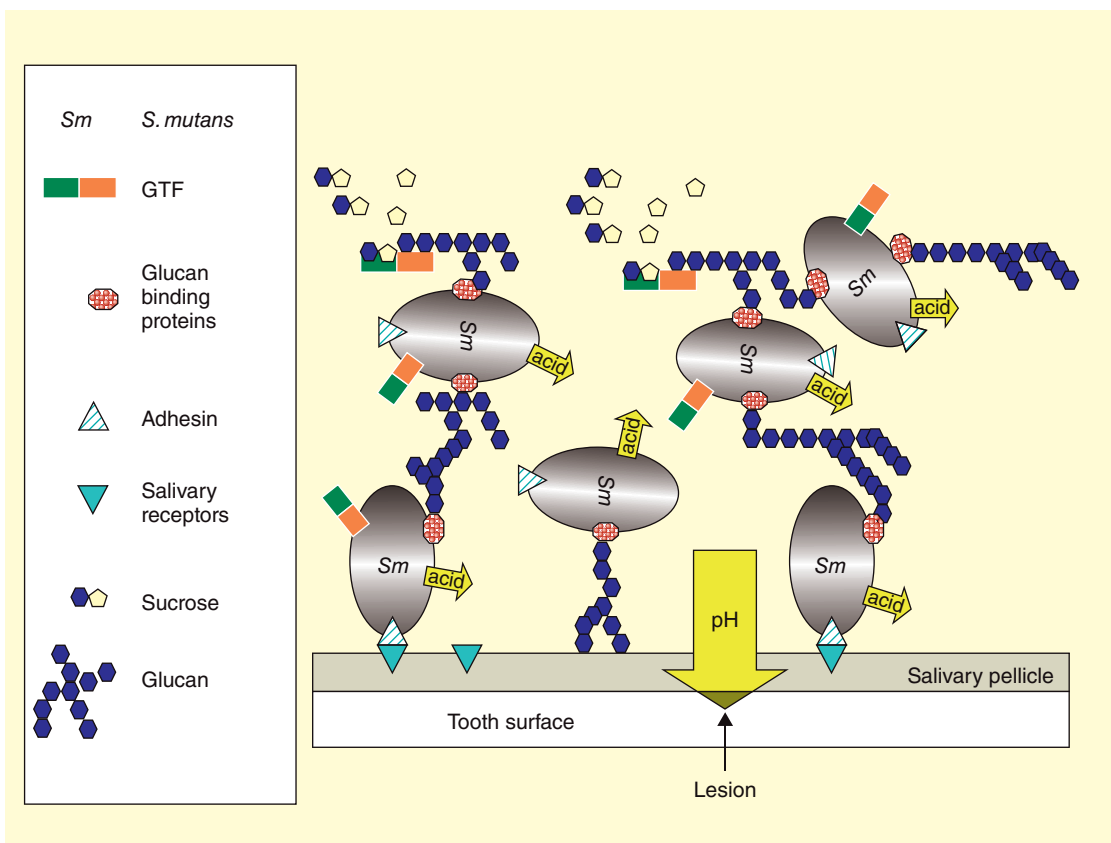


Fig. 9.1 Attachment and accumulation of *Streptococcus mutans* in the oral biofilm on the tooth surface.

nutrients from gingival crevicular fluid, rather than saliva. Paster *et al.*⁷ have identified approximately 500 subgingival bacterial species, although these species are not uniformly distributed. In healthy subjects, the numbers of most species are lower at subgingival, compared with supragingival sites. *A. naeslundii* is the dominant species in healthy (shallow) subgingival sites. Distinct species associations have been reported in different subgingival biofilms of health and disease². In health, the proportions and associations of species are fairly similar at supra- and subgingival sites. Both are dominated by *Actinomyces*, *Streptococci*, *Capnocytophaga* and *Veillonella* species. The subgingival biofilm(s) of disease are characterized by different bacterial associations¹². For example, *Camphylobacter*, *Fusobacter* and certain *Porphyromonas* species are often detected in the loosely adherent subgingival biofilms in diseased subjects. Most consistently associated with periodontal disease are epithelia-associated microorganisms of the so-called 'red complex' (*Porphyromonas gingivalis*, *Tannerella forsythia* and

Treponema denticola). Changes in available nutrients, bacterial coaggregation and proteolytic activities, epithelial surface area and inflammatory factors all influence the changes from habitats of health to those of disease.

SALIVARY COMPONENT INTERACTIONS WITH ORAL BACTERIA

A variety of host factors borne by saliva influences bacterial attachment, survival or growth on dental surfaces. The effects of saliva-borne factors on bacteria are manifest both in the planktonic (bulk fluid) phase and in the biofilm which coats the teeth and supporting structures. This salivary coating has been termed the 'salivary pellicle' and forms on the teeth soon after eruption. Thus, much of the initial bacterial interaction with the teeth is not with the hydroxyapatite surfaces themselves, but with the salivary protein and glycoprotein components within the pellicle.

Most organic salivary components interact with bacteria in some way. Several salivary proteins/glycoproteins function through direct binding of polypeptides on bacterial cell walls or extracellular structures. One example of this phenomenon is the interaction of the salivary agglutinin glycoprotein, gp340. This glycoprotein can interact with the so-called antigen I/II family of cell wall-anchored adhesins found on several oral streptococcal species, including those that have been implicated in dental caries¹³. Some of these oral streptococci (e.g. *S. mutans*) display but one type of antigen I/II. In contrast, *S. gordonii*, which preferentially colonizes the oral epithelium, displays two different antigen I/II polypeptides¹⁴. If gp340 agglutinin-antigen I/II interactions occur in the fluid phase, then bacteria are aggregated and swallowed, lowering their colonization potential. If this salivary agglutinin is sequestered in the biofilm and appropriate nutrients are available for bacterial growth and multiplication, interaction between gp340 and antigen I/II polypeptides can lead to bacterial accumulation within the biofilm. There is evidence to suggest that the bulk fluid phase interaction is different from binding which occurs in the biofilm. This difference in bacterial interactions in the fluid versus biofilm phase is, in fact, an important feature of biofilm physiology.

Salivary mucins (MG1 and MG2) are critical to oral health. These carbohydrate-rich glycoproteins are secreted by acinar cells of major (submandibular and sublingual) and minor salivary glands and have many protective and lubrication functions within the oral cavity. Of the two mucins, the MG2 is principally implicated in bacterial interactions, for example with Gram-positive oral streptococci, and with Gram-negative *A. actinomycetemcomitans* and *Eikenella corrodens* organisms associated with subgingival biofilms leading to periodontal diseases. Binding may involve interaction with both protein and carbohydrate determinants. Some of these interactions seem to require additional components since binding is lost on purification¹⁵. However, purified MG2 retains the ability to combine with the dental pathogen *S. mutans*, and also exhibits anticandidal activity in this form¹⁶. Presumably these binding features promote removal of bacteria and fungi from the oral cavity by swallowing.

Other salivary proteins, whose ability to interact with bacteria is different in salivary fluid and dental

biofilms, are the proline-rich proteins (PRPs) and statherin¹⁷. These small, acidic proteins inhibit crystal growth in the normal salivary condition of calcium phosphate supersaturation. PRPs and statherin bind to the dental enamel during pellicle formation. As a result of this process, an epitope, or epitopes, are exposed, permitting recognition of *Actinomyces* species, which are prominent commensal organisms of the oral cavity. This epitope(s) is cryptic when PRPs are in the fluid phase of saliva, hence its designation as a 'cryptitope'. Since significant concentrations of most salivary proteins exist early in life, these interactions might be part of the selection process of a healthy oral flora. Interestingly, however, the fimbriae of the periodontal disease-associated *P. gingivalis*, also bind to PRPs and statherin, albeit by different binding domains¹⁸. Antiviral activity has been reported for PRPs in that they have been shown to inhibit HIV-1 infectivity *in vitro*, possibly through binding to the HIV-I gp120 viral coat protein¹⁹.

Several salivary proteins affect bacteria, and thus their ability to incorporate into the oral biofilm, in ways not primarily related to attachment or binding of surface structures. Lactoferrin, an 80 kDa product of the salivary gland acinar and epithelial cells, is an iron-binding protein (two atoms/molecule). Many bacteria have an iron requirement for their metabolism and growth. By withholding metabolically essential iron, lactoferrin can thus limit the emergence of such bacteria in oral environments reached by this salivary protein. Iron-free lactoferrin has also been reported to have bacteriocidal effects on oral pathogens such as *P. gingivalis*²⁰. Peroxidases appear in oral fluids as a result of synthesis by salivary epithelial cells and from neutrophils present in the crevicular spaces. These proteins produce highly reactive hypothiocyanate ions in the presence of thiocyanate and bacterially generated peroxidase in saliva. The result for susceptible bacteria is oxidation of sulfhydryl groups on metabolic enzymes, thus inhibiting growth. This places affected organisms at a selective disadvantage in the oral environment. Lysozyme, a 14 kDa protein, is also produced by the salivary epithelium. This enzyme cleaves the beta-1,4 linkage between N-acetylmuramic acid and N-acetylglucosamine in the peptidoglycan of cell walls of Gram-positive bacteria. This effect can be bacteriocidal since lysis of cells can ensue. Secondary antibacterial effects have been described for these

proteins, including bacterial aggregation and clearing, generation of lethal hydroxyl radicals, and potential synergy with each other or with salivary SIgA antibody activity.

Histidine-rich basic peptides, or histatins, represent another group of salivary products with antimicrobial activity²¹. These peptides are secreted by parotid and submandibular glands and have antifungal properties, especially the 24 residue post-translationally modified histatin 5. Their cidal activity has been most thoroughly studied with *Candida albicans* and *Cryptococcus neoformans*. Histatin 5 is thought to function via binding to yeast membrane proteins resulting in non-lytic release of cellular stores of adenosine triphosphate (ATP), which may then activate mechanisms leading to cell death²². Although histatins undergo considerable degradation from bacterial and host proteases in whole saliva, significant antifungal activity is retained²³. Again, *in vitro* analyses suggest other bacterial interactions for histatins, including interference with *P. gingivalis*–*S. mutans* coaggregation and bacterial enzyme inhibition.

Other host-derived peptides found in the oral cavity have also been shown to have antibacterial properties. Among these are the defensins and cathelicidin, LL-37²⁴. Human beta defensins (hBD 1–4) are secreted by gingival epithelium and salivary glands. In contrast, alpha defensins are chiefly derived from polymorphonuclear leukocytes, thus are also known as human neutrophil peptides (HNP1–4). Both hBDs and HNPs have three disulfide bonds. Cathelicidin, also primarily a neutrophil product, contains one disulfide bond. The antibacterial effects of hBDs and cathelicidin are broad, having been shown to target *S. mutans*, *S. sanguinis*, *F. nucleatum*, *A. actinomycetemcomitans*, *Capnocytophaga sputigena* (cathelicin) and *P. gingivalis*. As with many peptides and glycoproteins in saliva, the antimicrobial activity of these peptides is apparently enhanced by synergies with other secreted components.

ADAPTIVE IMMUNITY IN THE ORAL CAVITY

The innate immune properties of many salivary proteins listed above are complemented by expressions of adaptive immunity in the oral cavity. Secretory immunoglobulin A (SIgA) antibody is the principal

immunoglobulin secreted in saliva. Salivary SIgA-derived immune responses are generated in mucosa-associated lymphoid tissue (MALT) by exposure to bacterial antigen. IgA-committed B-lymphocytes then migrate through the lymphatic system into the circulation where they home via addressins (e.g. MAdCAM-1) to mucosal sites including the oral cavity. Once in the local salivary gland tissue these lymphocytes mature to terminally differentiated IgA antibody-secreting plasma cells. Upon secretion, IgA antibody dimers bind to poly-immunoglobulin (poly-Ig) receptors on the surface of salivary epithelial cells. This complex is then endocytosed and transported to the apical region of the cell where SIgA is released into the salivary gland lumen, together with a portion of the poly-Ig which is covalently attached in the form of secretory component.

Both major and minor salivary glands secrete SIgA antibody into the oral cavity. This immunoglobulin class predominates in major salivary gland secretions. However, minor salivary glands (MSG) also contribute significant concentrations of IgG (labial) and IgM (palatine) classes to whole saliva. Since these immunoglobulin classes have some primary and secondary interactions which are distinct from SIgA, expression of immunity within the secretory microenvironments of MSG may not be the same at different oral sites. The relatively short, broad secretory ducts of minor salivary glands have also been suggested to provide pathways for local exposure of lymphatic tissue via retrograde passage of bacterial antigens from the oral biofilm.

SIgA antibodies which are thus secreted into saliva contain a multitude of immunological specificities directed against bacterial components in the oral biofilm as a result of antigenic stimulation in the gut-associated lymphoid tissue (GALT), as well as more local inductive lymphatic sites in Waldeyer's ring. Salivary antibody to microorganisms that colonize the oral cavity can be detected within the first few weeks of life. Antibody specificities to these pioneer microbiota become more diverse as children age and salivary SIgA concentrations increase. During these early years of life habitats become more complex because of biofilm maturation, because fresh surfaces for colonization appear via tooth eruption and because of an increased variety of food intake and independence of action. Consequently, the oral biofilm 'membership' increases to

the manifold numbers and complexity seen in adults. The resulting antigenic exposure also results in a considerable amplification in salivary IgA antibody specificities.

The role of antibody at mucosal surfaces, particularly in the microorganism-rich oral cavity is probably more complex than its role in systemic locations where sterility is the goal. Consequences of local secretory immune responses may be removal of bacteria in the bulk fluid phase by binding epitopes on the bacterial surface or interference with a variety of activities necessary for microbial incorporation into the oral cavity. Many biotypes of oral microorganisms may be present in oral bacterial challenges, but those that go on to successful colonization are quite limited. This refinement in which biotypes of commensal flora populate the oral cavity may result, in part, from combination with complementary oral epithelial receptors and/or with polymorphic salivary peptides in the pellicle. However, also playing a role in this process may be the salivary antibody response induced by previous exposure to bacterial biotypes in earlier challenges. Antibody specificity and avidity, as well as the physical location (bulk fluid or biofilm) may each modulate the microbial composition of the oral biofilms, albeit in different ways.

Biofilms above and below the gingival margin are also exposed to immune components in the gingival crevicular fluid (GCF). When periodontal disease is present, crevicular fluid increases in complexity of components and in flow. The principal antibody in this habitat is IgG; much smaller concentrations of IgA are also present. This fluid also contains a number of accessory components of immunity such as complement. In addition, GCF is rich in cellular elements, especially polymorphonuclear leukocytes. Thus many diverse immune activities, including complement fixation and opsonization, are possible following exposure of bacteria to primed immune responses. Furthermore, immune cells can release enzymes into the fluid milieu following bacterial interaction. These components, myeloperoxidases for example, can be bacteriocidal as described above. The immunologically triggered sequelae of IgG-mediated antigen recognition occur principally in the crevicular space and cervical areas of the teeth and not in whole saliva where complement concentrations are quite low. Activities of immune cells are also compromised in whole saliva because of its

hypotonicity. The GCF is also a source of nutrients to microorganisms in both the sub- and supragingival biofilms. Thus the GCF can play several roles in the maintenance and diversity of oral biofilms in health and disease.

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10

Salivary Levels of Cariogenic Bacteria in Patients Treated with Self-Ligating and Conventional Brackets

William Papaioannou, Nikolaos Pandis and Theodore Eliades

INTRODUCTION

Orthodontic therapy is one of the most common dental interventions performed primarily, but not restricted, to adolescents and young adults in order to correct problems of occlusion. Therapy most often includes the placement of orthodontic brackets and wires held together via elastomeric or stainless steel ligatures. Although self-ligation in orthodontics appeared several decades ago, the first commercially viable system, the SPEED bracket, was not introduced until the early 1980s. A small number of self-ligating brackets appeared thereafter but none of them received widespread acceptance. However, the late 1990s was a turning point for self-ligation and today almost all major orthodontic companies list them among their products¹.

The oral cavity is a rich ecosystem with a plethora of microorganisms comprising the inhabitants of this aquatic system. The soft and hard oral tissues are normally in a state of balance with the bacteria and the oral environment, in which case health is maintained. In this state of balance the bacteria that may cause disease, when present, are usually found at lower concentrations. The most common oral diseases in man are caries and periodontal disease. Although both are considered multifactorial diseases, plaque bacteria are the major factor in their onset and progression. There are, however, situations (that comprise what Marsh² has called ecological stress) that may cause this balance to change in favor of conditions conducive to the growth and appearance of cariogenic and/or periodontopathic bacteria.

The different parts of the fixed orthodontic system may contribute to change in the balance of the oral ecology. Much concern, as well as research, has been

shown over the years due to the intimate contact the orthodontic materials have with the tooth and periodontal tissue. Indeed, the presence of brackets and ligatures has been shown to be related to increased gingival inflammation and increased risk for decalcification, which may affect up to 50% of patients. Indeed demineralization of the dental surfaces results in the appearance of white spot lesions or even carious lesions. One of the proposed advantages of self-ligating brackets is their beneficial effect on plaque accumulation; however, data supporting this claim are scarce.

This chapter will discuss numerous factors that may be associated with microbial-induced demineralization and dental caries in conjunction with fixed appliance orthodontic therapy, and with different bracket systems.

EFFECT OF ORTHODONTIC THERAPY ON ORAL CARIOGENIC BACTERIA

The dental literature suggests that orthodontic treatment with fixed appliances leads to increased plaque accumulation³ and bacterial counts^{4,5}. Plaque retention is facilitated by the complex surface of the brackets and the retentive areas formed by these as well as the archwires, ligatures, bands and cementing material. At the same time the performance of efficacious oral hygiene is hindered⁶, especially considering the young age of most orthodontic patients. The increase in plaque retention may cause gingival swelling and overgrowth in many patients further hindering plaque removal.

Increased dental plaque levels in orthodontic patients have been related to qualitative changes in

the oral microbiota, resulting in elevated levels of mutans streptococci and lactobacilli which are considered to be the main pathogens in dental caries^{5,7}. Specifically, a higher frequency of colonization by mutans streptococci was reported for caries-free children undergoing orthodontic therapy compared to a matched, caries-free, control that had never undergone orthodontic therapy⁸, suggesting *Streptococcus mutans*-rich oral biofilm formation (Fig. 10.1)⁹. Jordan and Leblanc¹⁰ investigated the effect of orthodontic therapy on *S. mutans* counts, and found that for the majority of the patients they examined, the increase between baseline and 4 months after bonding remained within one log score difference. In the same study it was found that again for the majority of patients all isolates examined represented the same clone of *S. mutans*.

Detailed knowledge concerning the initiation of carious lesions as well as available options for their prevention is an important concern to the orthodontist. Factors that may have an impact on the formation of the oral microflora are of great interest, and are related to: (a) the bonding material and its characteristics, (b) the material composition of the brackets, and finally (c) the bracket design and type of ligation.

Effect of the bonding material

The bonding material used to maintain the brackets attached to the tooth surface may affect plaque

growth and retention of bacteria. This can be due to the surface characteristics of the material used but also by the junction formed between the tooth surface and the bonding material which can provide the initially adhering bacteria and immature plaque biofilm protection from removal forces¹¹. Normally, composite resins are used for the bonding of brackets, but glass ionomer cements are also used in fixed orthodontics. Their relationship with the development of white spot and even caries lesion is not hard to envision considering the intimate contact with the hard tooth tissues and the opportunity they offer for bacteria to adhere¹²⁻¹⁴. This was illustrated by Sukontapatipark *et al.*¹⁵ in their scanning electron microscopy study. They found that excess composite around brackets harbored a mature plaque biofilm while the surrounding enamel surface had plaque in only the early stages of development.

Maturation of the dental plaque makes it easier, and is even a prerequisite, for specific pathogens to appear and multiply. In a study by Örtendahl *et al.*¹⁶ the presence of mutans streptococci was examined around brackets retained by either a resin-based composite or glass ionomer cement in 11 full-term orthodontic patients using a split-mouth design. They found lower numbers of mutans streptococci around the brackets retained by glass ionomer cement. Even though this difference was found to be in excess of a log score (1.9×10^4 vs 2.4×10^5 colony forming units, for glass ionomer and resin respectively) it was not found to be statistically

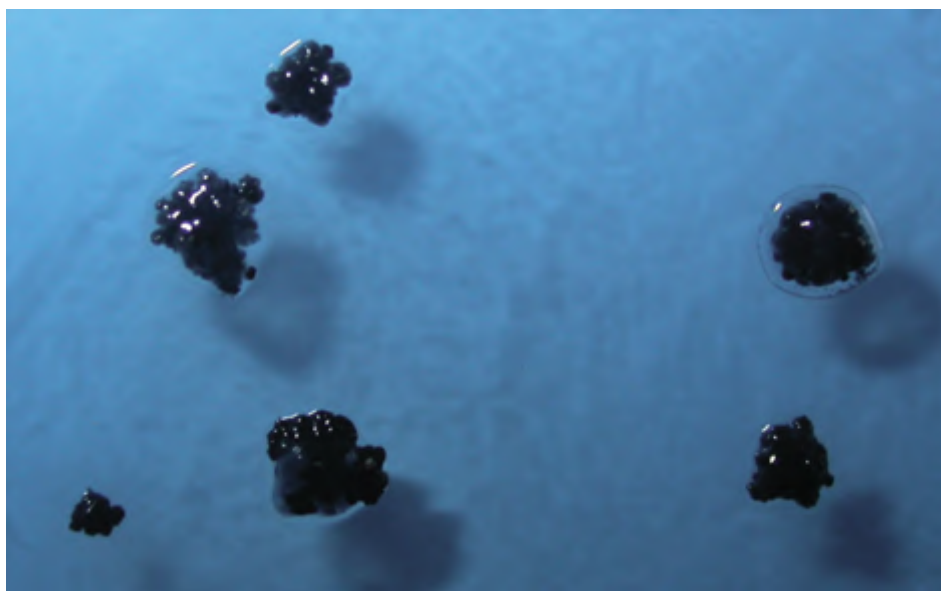


Fig. 10.1 *Streptococcus mutans* colonies grown on MSB agar. Notice the clear drop-like material covering the colonies which is the extracellular polysaccharides, a characteristic of this bacterium.

significant. Two of the subjects were found to also harbor *Streptococcus sobrinus*. Moreover, these two patients were the only ones to develop early caries lesions. Interestingly, they report that these lesions developed in the vicinity of the resin-bonded brackets.

The abovementioned findings are in agreement with another short-term study (up to 28 days after the start of therapy) with a similar split-mouth design, where a less caries-associated microbiota was discovered when glass ionomer cements were used¹⁷. *In vitro* experiments confirm the antibacterial properties of glass ionomer cement, found to be superior in potency and time of activity, to other common commercial bonding material¹⁸. However, it must be remembered that the other bonding materials also have an antibacterial effect, albeit to a lesser degree^{18,19}.

Attempts have been made to increase the antibacterial effect of adhesives by incorporating chemical agents to enhance this characteristic. An antimicrobial effect has been shown *in vitro* with the addition of benzalkonium chloride (BAC) to chemically cured composite resin²⁰. In a more recent study this antimicrobial, BAC, was found to be more effective than even chlorhexidine or triclosan as additives to composite resin²¹. Commercially BAC is primarily used as an additive to contact lens rinses.

Cetylpyridinium chloride (CPC) is another quaternary ammonium compound, as is BAC, which has been examined extensively as an adjunctive antimicrobial, primarily as an oral rinse^{22,23} but also as a non-degradable osmotic slow-release device²⁴ and chewing gum²⁵. In an *in vitro* study²⁶ that examined the antimicrobial properties of an orthodontic adhesive combined with different concentrations of CPC, inhibition of *S. mutans* was recorded for a period of up to 196 days (the total duration of the study). When considering adhesives, it is important to take into account the effect such an addition may have on its physical properties. The previous study found that concentrations higher than 2.5% CPC lowered the tensile strength of the adhesive examined, while at the 2.5% level sufficient antimicrobial activity was imparted to the material.

It is clear that the enrichment of the different orthodontic adhesives with antimicrobial compounds is promising. However, the data available is still relatively poor and primarily at the *in vitro* experimental level. Studies examining the effect at a

clinical level would be of great interest and should be encouraged.

Effect of orthodontic bracket material

The bracket material could play a role in the degree of bacterial adhesion and plaque accumulation and consequently influence the risk of caries development. The initial affinity of bacteria to solid surfaces is mostly due to electrostatic and hydrophobic interactions, whilst surfaces with high surface free energy attract bacteria such as *S. mutans* more easily²⁷. In a study by Eliades *et al.*²⁸ stainless steel exhibited the highest critical surface tension and was expected to have a higher plaque retaining capacity. Additionally, metallic orthodontic brackets have been found to induce specific changes in the oral environment, such as reduced pH levels, increased plaque accumulation and elevated *S. mutans* colonization. Nevertheless studies on the possible differences in the initial affinity and adherence of bacteria on metal, ceramic and plastic brackets over time were inconclusive^{29,30} and often contradictory.

In a recent *in vitro* study by Papaioannou *et al.*³¹, the adhesion of a clinical strain of *S. mutans* to brackets of different composition was examined. Three adhesion experiments were conducted using stainless steel, ceramic and plastic orthodontic brackets. In the first experiment a clinical strain of *S. mutans* adhered to the three different types of brackets (Figs. 10.2, 10.3). In the second trial, all bracket types were treated with saliva before adhesion of *S. mutans*. Finally, in the third experiment, on saliva-coated brackets, *Streptococcus sanguinis* bacteria were allowed to adhere before the adhesion of *S. mutans*. It was clear from the results that there were consistently no significant differences in the adherence of *S. mutans* to the three different types of brackets. Normally, for non-coated brackets, only the surface characteristics should determine adhesion of bacteria, which would suggest that bacteria with high surface free energy such as *S. mutans*³² should prefer surfaces with high surface free energy materials such as stainless steel brackets²⁸. However, this is not corroborated by the available studies²⁹⁻³¹.

Other factors of the oral environment may further decrease any possible differences due to the different surface characteristic. One such important factor for

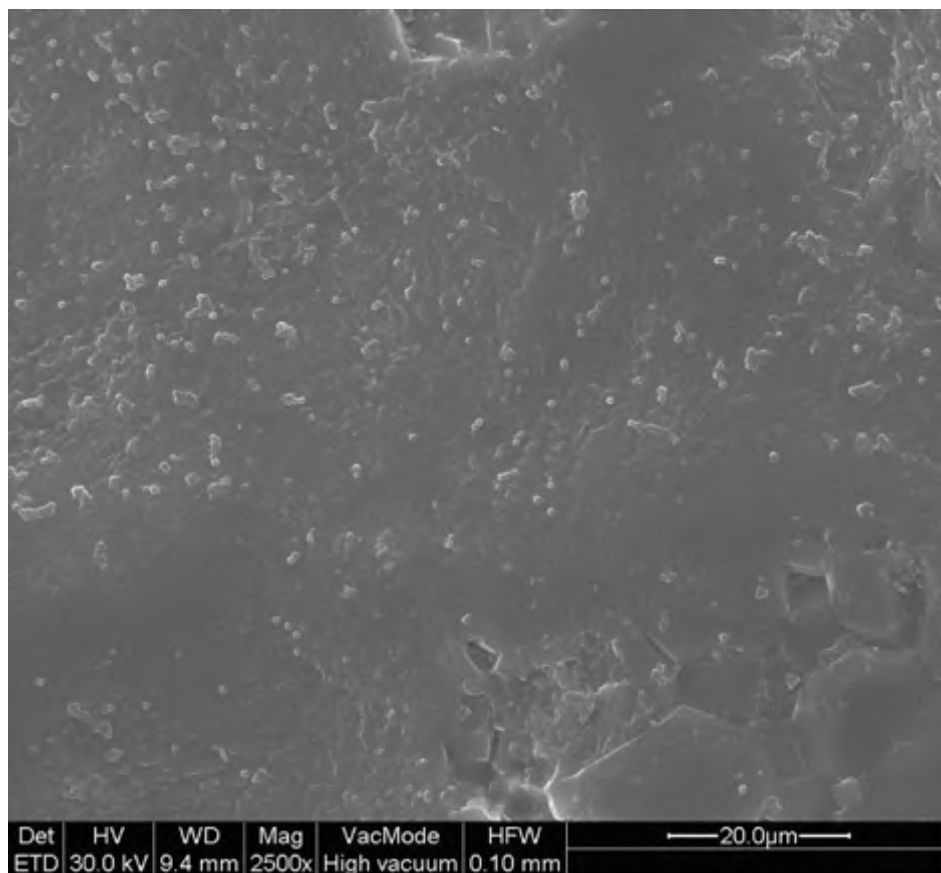


Fig. 10.2 Adhesion of *S. mutans* bacterial cells to the surface of a plastic orthodontic bracket as seen by scanning electron microscope.

the microbial colonization of oral hard surfaces is the salivary or acquired pellicle which can form not only on tooth surfaces but also on restorations, prosthetic and orthodontic appliances. Therefore the adhesion of oral microorganisms to the bracket surface may be influenced to a large extent by interactions between salivary components in the pellicle and properties of the different microorganisms, in addition to the adherent patterns of bacteria on the different types of orthodontic brackets. The presence of even an early salivary pellicle, as in the second experiment above, was found to reduce the number of adhering bacterial cells of *S. mutans*^{29–31}. This may be explained by the fact that coating a surface with saliva reduces the surface free energy of the underlying materials¹¹, even within 30 minutes of pellicle formation.

Finally, the third experiment examined another important factor for bacterial adhesion; the interaction between different bacterial species in adhesion to a surface. Specifically, *S. sanguinis*, one of the initial colonizers of the oral cavity was found to

further reduce the number of adhering *S. mutans* regardless of the type of surface. *S. mutans* and *S. sanguinis* would seem to have an antagonistic relationship and an early colonization by the latter may have a significant effect on concentrations of *S. mutans*³³. A delayed colonization by mutans streptococci may lead to less caries or caries susceptibility³⁴.

It would seem that the adhesion of bacteria to the surface of orthodontic brackets depends on several factors. The presence of a salivary pellicle and other bacterial species appear to have a significant effect on the adhesion of *S. mutans*, reducing their numbers and further limiting the differences between the different surfaces. Therefore it is difficult to make a clear assessment that certain brackets, i.e. metal brackets, have a lower cariogenic effect on the teeth than plastic or ceramic brackets. Even the amount of time that the bacteria have available to adhere may affect the results. *S. mutans* adherence, for example, has been shown to increase with longer incubation times³⁵. But, for this factor too the oppo-

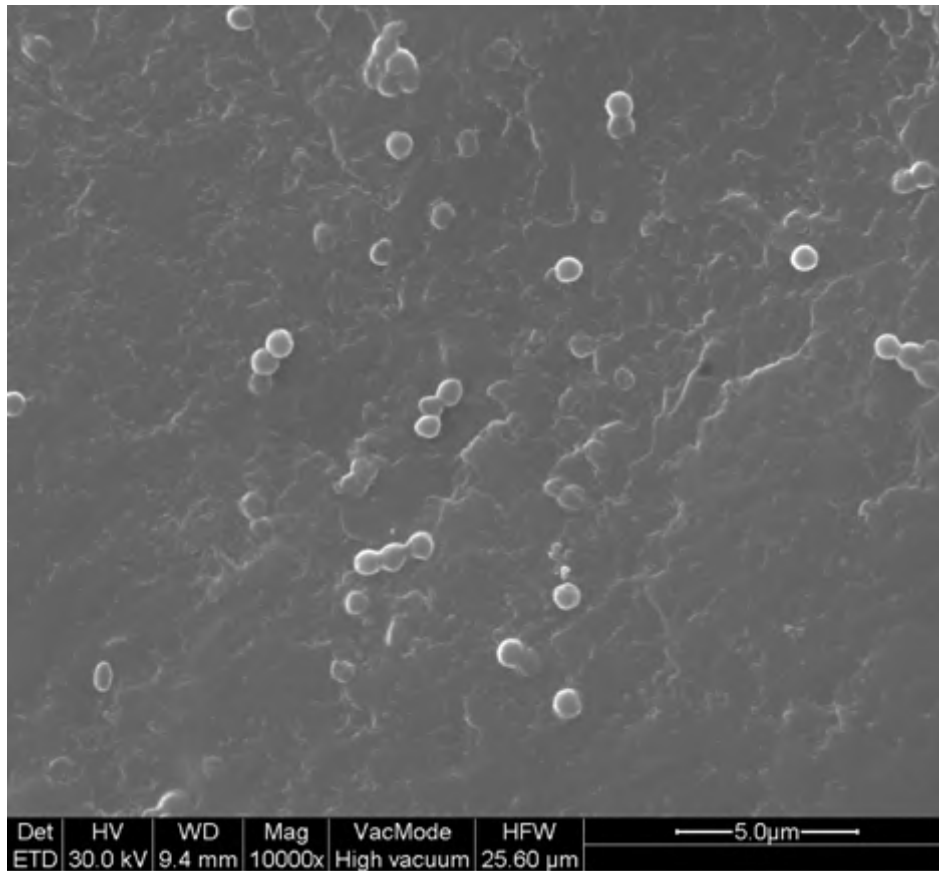


Fig. 10.3 Adhesion of *S. mutans* bacterial cells to the surface of a plastic bracket seen by scanning electron microscope at a higher magnification (1000×). Notice the formation of short chains of streptococcal bacteria.

site has been shown, with a decrease in the affinity of bacteria for the brackets over time²⁹. Finally, a factor that may play a role in adhesion (and especially in clinical situations) is the size and different shapes of available brackets that may provide retentive surfaces for the formation of dental plaque.

Bracket design and ligation mode

The morphology and architecture of the orthodontic bracket, as well as the ligation mode, may play a role by providing new areas of retention and protection from plaque-removal forces thus facilitating dental plaque accumulation and maturation. One of the proposed favorable aspects of self-ligating brackets is associated with the elimination of elastomeric or stainless steel ligatures. This feature brings two basic advantages: the eradication of cross-contamination, which may accidentally be involved in the process of ligature change, and the claimed

improvement in the oral hygiene of patients. The latter has been attributed to the fact that the patient is given the opportunity to clean surfaces of reduced complexity and with less retentive sites for microbial colonization.

Teeth ligated with elastomeric rings have been found to harbor, in the area of the brackets, higher numbers of bacteria than those where steel wire was utilized⁷. The type of bacterial morphotypes, as seen in a scanning electron microscopy study, was not however found to differ between the two ligation methods¹⁵.

In a recent study, Türkkahraman *et al.*³⁶, implementing a split-mouth protocol, examined the effect of the two ligation modes (elastomeric rings and ligature wires) on the accumulation of specific cariogenic species (*S. mutans* and lactobacilli) as well as the periodontal status, before therapy and at 1 week and 5 weeks after the start of therapy. Slightly higher total counts of bacteria around the elastomeric rings were found that did not reach statistical significance, however, even though in all 21 patients

significant increases of bacteria counts were recorded. Finally, elastomeric rings appeared more conducive to gingival bleeding, perhaps due to their slightly higher affinity to plaque. For this reason the authors suggested that the use of elastic ligatures should be avoided in patients with inadequate oral hygiene.

In a recent study the effect of the type of bracket (conventional vs self-ligating) on the salivary levels of *S. mutans* in two groups of patients undergoing fixed appliance orthodontic therapy was investigated³⁷. Thirty-two young patients were selected from a larger pool of patients from a private orthodontic practice using the following inclusion criteria: adolescents (mean age 13.6, range 11–17 years) and fixed appliances on both dental arches. Consecutive patients who fulfilled the aforementioned criteria were registered for the study, randomly, as they visited the office to commence orthodontic treatment. They were subdivided in two equal size categories based on bracket type used, i.e. conventional (Microarch, GAC International, Central Islip, New York, USA), or self-ligating (In-Ovation R, GAC International, Central Islip, New York, USA). Routine oral hygiene instructions with specific care for the orthodontic appliances were provided at the beginning of treatment as per the treatment protocol for every orthodontic patient. No dental prophylaxis therapy, brushing or other hygiene measure was applied immediately prior to examination.

For both groups, the following clinical variables were assessed for each child: the simplified Plaque

Index (S-PII), where only the presence or absence of plaque is recorded for the six surfaces of all erupted teeth, to determine the level of oral cleanliness and the DMFT index. Plaque-disclosing solution was not used. Both indices were recorded at each visit.

Whole saliva was collected, from each child at two time points. Saliva sampling was performed before orthodontic therapy was initiated (baseline) and at 2–3 months after the placement of brackets and the start of orthodontic therapy. At each of these time points, each subject was asked to expectorate approximately 3 ml of saliva into chilled petri dishes. The collection of saliva was performed before any oral examination or manipulation was performed so as not to disrupt the oral microbiota. Serial 10-fold dilutions of the saliva samples were inoculated on a selective growth media for *S. mutans* (Fig. 10.1). The medium used was Mitis Salivarius agar supplemented with sucrose (20% w/v), bacitracin and tellurite solution (MSB). Plates were incubated for up 7 days in CO₂ atmosphere at 37°C.

Both groups showed similar levels of dental status oral hygiene, which remained steady during the first 3 months of therapy. However, the levels of *S. mutans* increased for both groups of children, as has been previously shown for fixed orthodontic therapy (Fig. 10.4). This was a general trend and irrespective of bracket type, but without reaching a level of statistical significance. Slight differences were seen between the two groups of patients, with slightly

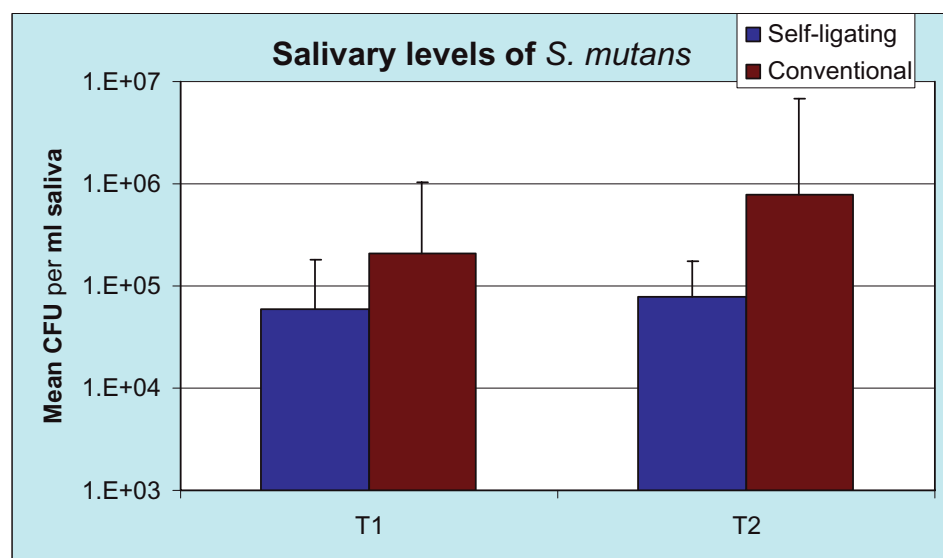


Fig. 10.4 Salivary levels of *S. mutans* for the two time points and for the two groups of patients under orthodontic therapy. Results are expressed in total number of *S. mutans* CFU per ml of saliva. Data from Pandis *et al.*³⁷

higher numbers of *S. mutans* in the conventional bracket group, but no statistically significant differences could be discovered. An interesting finding of this study was that the pretreatment levels of *S. mutans* in saliva were significant predictors of the levels of *S. mutans* found after placement of orthodontic appliances, and at the time the second sample was taken.

Although the mode of ligation may have an effect on plaque build-up and/or on the increase of specific bacterial species, the importance of the type of ligation on bacterial accumulation is not yet fully explained. The simplest approach to eliminate any effect elastic rings may have on the oral microbiota is simply by reducing their use, and self-ligating brackets make the use of elastic rings unnecessary. However, the overall effect on the oral microbiota is unclear. As presented above, the oral concentrations of *S. mutans* were found to be slightly higher in patients with conventional brackets compared to self-ligating but this difference did not reach a level of significance. Locally though, i.e. in the tissues immediately in the vicinity of the brackets, there may be an effect. An important effect of bracket type on periodontal tissues and microbiological parameters is discussed in Chapter 11.

Other approaches to alter the relationship between elastomers and dental plaque accumulation include the use of fluoride releasing elastomers³⁸⁻⁴⁰. Stannous fluoride is the fluoride of choice when the focus is on bacteria, due to the antibacterial properties it possesses^{41,42}. A significant decrease in salivary levels was found when fluoride-releasing elastomers were placed in a group of orthodontic patients, however there was no significant effect after 2 or more weeks of the elastomers remaining in place³⁸. In a more recent split-mouth crossover study⁴⁰ that examined the bacteria that the elastomers themselves retained after 6 weeks of intraoral presence, there were no significant differences for either streptococcal or anaerobic bacteria growth in cultures.

Even the effect on the hard tissues has been found to be negligible with significant increase in microhardness of enamel found only up to 20 µm in depth³⁹, while no significant anticariogenic effect was found in an *in situ* caries model⁴³. The failure to detect significant effects in either antibacterial effect or inhibition of demineralization by the use of fluoride-releasing ligatures can be ascribed to the short time period that the fluoride is released.

A major problem in fixed orthodontics is the development of white spot lesions, or even full carious lesions, due to the demineralization of enamel around the adhering brackets. The number of affected patients reaches 50% or even 70%⁴⁴. Thus the prevention of demineralization is of great importance during the treatment period. Daily mechanical plaque control is the main preventive measure without question, however due to the increased retentive characteristics of the orthodontic appliances and impaired plaque removal, as discussed above, means of altering the local and general oral conditions are of interest.

The adhesion of bacteria to brackets would seem to be complicated, especially in the oral cavity where interactions between the salivary pellicle, the many different bacteria, and bracket's surface characteristics take place. There are possibly many more factors that cannot be examined easily *in vitro*. Future clinical studies of the oral health and microflora between patients wearing different types of brackets would help determine any difference of clinical importance in the plaque composition and the cariogenic effect of each type of bracket on the oral health of the orthodontic patient. It must be pointed out here that an increase in mutans streptococci does not indicate a prediction of caries development but of increased risk of development.

From the findings of the study by Pandis *et al.*³⁷, the hypothesis that the self-ligating bracket should have a beneficial effect due to the absence of ligatures, is rejected. Based on these findings, the ecology of the oral cavity does not seem to be significantly altered. Locally though the situation may be totally different and there may be an effect. But the data for the microbiological and clinical effects of self-ligating brackets are extremely poor. As was already mentioned, only one other study is presently available, and that focuses on periodontal factors and associated bacteria. In this study, by Van Gastel *et al.*⁴⁵, which is summarized in Chapter 11, an important local effect of bracket type was found. Indeed, at the area around the brackets there were significant alterations in both periodontal and microbiological parameters with the self-ligating SPEED brackets even obtaining worse scores.

The results of available studies agree that orthodontic therapy exerts 'ecological stress' on the oral ecosystem which in turn results in increases of certain bacterial species. There are, though, conflicting

results on the degree that bracket design parameters may affect the bacterial colonization of orthodontic appliances. From the results presented in this chapter it may be determined that these parameters may have only a negligible effect. This could be attributed to the implementation of an oral hygiene program, which is taught at the early stages of orthodontic treatment. However, the fact that the initial concentrations of *S. mutans* did exert a significant effect upon the increase of this bacterium over time, may be an important factor to take into consideration when determining the risk a specific patient may run of developing white spot, or even carious, lesions during orthodontic therapy. Thus, the emphasis should be placed on the importance of a more individualized preventive program for orthodontic patients involving rigorous plaque control, perhaps in combination with oral rinses containing substances such as sodium fluoride⁴⁶, or a combination of amine fluoride/stannous fluoride⁴⁷, or even chlorhexidine varnishes^{48–50}.

In conclusion, from the limited available research there is no validation that self-ligating brackets are more beneficial when it comes to bacterial accumulation, in comparison with conventional brackets and ligation methods. Again emphasis should be placed on daily efficacious plaque control. Research looking into alternative methods for prevention in this special patient group should probably be given more attention.

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11

Periodontal Impact of Orthodontic Treatment with Self-Ligating Brackets

Jan van Gastel, Marc Quirynen, Wim Teughels and Carine Carels

INTRODUCTION

The past decades have witnessed a steady increase of patients undergoing orthodontic treatment with fixed appliances¹. The majority of patients seek treatment for improvement of their orofacial esthetics, regardless of an objective medical or dental need, and at times it is difficult to evaluate whether the advantages of the orthodontic therapy are greater than the risks². Several indices have been developed to objectively score the treatment need, and although most indices include a dental health component, no periodontal need measurement is incorporated in the scoring.

Malalignment of the dentition is one of the possible dental justifications for orthodontic treatment, however there is a controversy about the impact of crowding and malocclusion on the accumulation and maturation of dental plaque^{3,4}. The etiology and pathogenesis of periodontal diseases are known to be multifactorial, but dental plaque certainly is an essential precursor. Hence, any factor that promotes plaque accumulation or makes its removal more difficult, might contribute to increased risk for localized periodontal disease. Orthodontic brackets and bands are known to be factors which increase plaque accumulation. Despite the widespread use of fixed appliances to solve orthodontic problems, the effect of bracket placement on periodontal health is not completely clear. Moreover there are no reports available on the periodontal changes during and after orthodontic treatment with self-ligating brackets.

SHORT-TERM EFFECTS

The placement of orthodontic attachments such as bands and brackets creates new retentive locations, increases plaque accumulation and thereby promotes the inflammatory response⁵. The microbiological changes after bracket placement became a topic of interest during the late 1980s. Initially cariogenic species such as *Streptococcus mutans* and *Lactobacillus* species and the subsequent decalcification of enamel were the main fields of interest among investigators^{6,7}. Later on, the more complex system of periodontopathic microbes and the changes after bracket placement became the main topics of interest⁸⁻¹⁰.

Earlier procedures, such as full banding, are known to lead to a generalized form of gingivitis within a short period of time, even with good oral hygiene (Fig. 11.1)^{11,12}. This reaction is characterized clinically by increased signs of inflammation, gingival swelling and pseudo-pocket formation, particularly at the proximal areas. The reductions in pocket depths following termination of active treatment are not accompanied by concomitant reductions in the distances to a stable reference point. This indicates that the increased probing depths during treatment are mainly due to edematous swelling and tissue accumulation during tooth movement, and not to an apical movement of the gingival pocket epithelium. Kouraki *et al.* followed 30 adolescent patients, who underwent orthodontic treatment for an average period of 27.5 months, and found gingival enlargements in all patients after



Fig. 11.1 Clinical example of a patient with a localized hyperthrophic reaction of the gingiva immediately after removal of the fixed orthodontic appliances. The increased probing depths are due to pseudo-pocket formation.

treatment completion¹³. The average percentage of papillae affected in a patient was 46% at bracket removal compared to 29% before treatment. After removal of the brackets a significant reduction in gingival enlargements was shown, but the values 2–3 months after treatment remained significantly higher than those before treatment¹³. Ramadan measured concentrations of chromium and nickel in saliva after the placement of fixed orthodontic appliances and their effects on gingival tissues during orthodontic treatment¹⁴. Three months after treatment initiation, 20% of females and 10% of males in his study showed gingival swelling which was explained as an allergic reaction. This gingival enlargement disappeared only partly 1 month after appliance removal. These studies are in disagreement, however, with other studies in which the gingival enlargement observed during orthodontic treatment (Fig. 11.1) was completely reversible upon removal of the orthodontic appliances for all patients examined^{5,12,15}. Although most authors agree that the changes during orthodontic treatment are completely reversible, some studies do report attachment loss during orthodontic treatment with fixed appliances^{16–18}.

The degree of gingival swelling can be used as an indicator of gingival inflammation. A reliable and earlier indicator of inflammation is the crevicular fluid flow ($\mu\text{l}/\text{min}$) and the cytokines present in this fluid. Cytokines present in the crevicular fluid have been shown to mediate the host's immunological responses to exogenous antigens¹⁹. Recently, it was found that they are also produced by connective

tissue cells such as fibroblasts and osteoblasts and are involved in normal physiological turnover and bone remodelling. Cytokines are low molecular weight proteins (<25 kDa) produced by cells that regulate or modify the action of other cells in an autocrine (acting on the cell of origin) or paracrine (acting on adjacent cells) manner. The definition includes the interleukins (ILs), tumour necrosis factors (TNFs), interferons (IF), growth factors (GF) and colony stimulating factors (CSF). A major difficulty in understanding cytokine biology is the sheer number and complexity of these factors. Another problem is that several factors, such as IL-1 and TNF, exhibit overlapping biological activities (redundancy) and many have multiple biological effects (pleiotropy). This makes it difficult to make a distinction between the cytokine response to inflammation and tooth movement during orthodontic treatment in clinical studies.

In a longitudinal study of gingival biopsies from buccal sites of molars, Zachrisson and Zachrisson demonstrated that shortly after the insertion of bands the gingival connective tissue was infiltrated by inflammatory cells¹². The dominant cell type in the first month was of the lymphocyte line, but there was a subsequent shift to plasma cells. The leukocytic infiltrate also differed regarding the topography of the different cell types; while plasma cells were located more centrally in the connective tissue, lymphocytes and polymorphonuclear leukocytes (PMNs) were located more superficially, close to the epithelium. After band removal the inflammatory gingival lesions gradually decreased, with acanthosis of the sulcus epithelium persisting sporadically¹². Diedrich *et al.* showed the histopathological image of an established gingival lesion: detached and severely damaged epithelial attachment, subgingival plaque, massive leukocyte infiltration (mainly lymphocytes, PMNs and plasma cells) and loss of collagen resulting in destruction of the intrapapillary fiber apparatus. The transseptal fibers, the last protective barrier against microbial aggression towards the alveolar margin, were permeated to varying degrees by cellular infiltrates especially at the interdental spaces due to subgingival position of the band margins. At one of these sites, the connective tissue attachment was severely damaged, resulting in apical migration of the pocket epithelium leading to a transition from chronic gingivitis to an initial irreversible periodontal lesion²⁰.

LONG-TERM EFFECTS

In order to elucidate the long-term effects of orthodontic treatment, Sadowsky and BeGole conducted a retrospective study in which they compared 96 subjects who had received orthodontic treatment during adolescence with a control group consisting of 103 subjects (matched for race, sex, age, socioeconomic status, oral hygiene and dental awareness) but with malocclusions that had not been orthodontically treated²¹. In general, they did not detect significant differences between the two groups in the general prevalence of periodontal disease, but a more detailed analysis showed that the subjects in the orthodontically treated group showed mild to moderate periodontal disease in the maxillary posterior and mandibular anterior teeth compared to the control group. The results suggest that orthodontic treatment in adolescence is not a major factor in determining long-term periodontal health status. Neither does the lack of orthodontic treatment in adolescence appear to influence subsequent development or non-development of periodontal disease in adult life²¹. Polson *et al.* drew the same conclusions after performing a comparable study in 112 orthodontically treated and 111 control subjects²². Davies *et al.* recorded plaque indices, bleeding indices and degree of dental irregularity of the front teeth in a group of 417 children either receiving or not receiving orthodontic therapy with occlusal variations and again after 3 years. There were significant reductions in the plaque and gingivitis scores on all dental surfaces between the baseline and 3-year examination in the two groups of children. The children who received orthodontic treatment had a greater reduction, but this appeared to be related to behavioral factors rather than to improved dental alignment²³.

DIFFERENT BRACKET SYSTEMS

Most of the studies concerning the influence of bracket placement show microbial changes accompanied by increased signs of gingivitis after banding and bonding of fixed orthodontic appliances. As the design and the material characteristics of orthodontic bracket types vary considerably²⁴, plaque adhesion and therefore the induction of gingivitis²⁵ might differ among currently used bracket versions. These

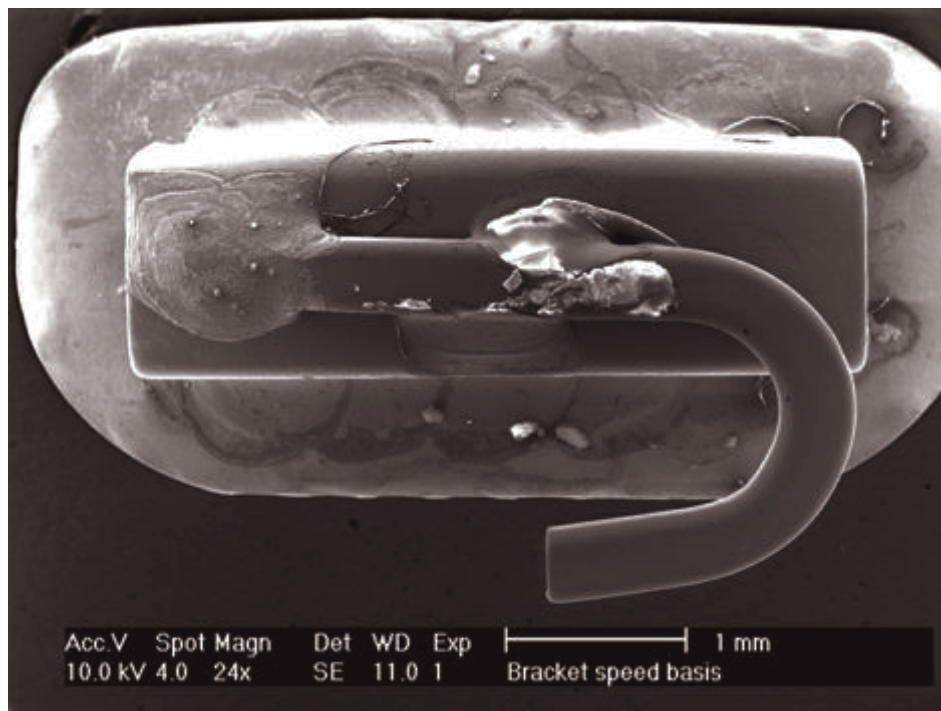
microbial and periodontal differences between the different orthodontic materials are not thoroughly studied. Türkkakraman *et al.* conducted a study to follow the changes in microbial flora and periodontal status after orthodontic bonding to investigate whether two different archwire ligation techniques affect these changes²⁶. For some time, elastomeric rings have been considered to give increased bacterial counts. Although teeth ligated with elastomeric rings exhibited slightly higher numbers of microorganisms than teeth ligated with steel ligature wires, the differences were not statistically significant and can be ignored. The two archwire ligation techniques showed no significant differences concerning the gingival index, plaque index or pocket depths of the bonded teeth. However, teeth ligated with elastomeric rings were more prone to gingival bleeding²⁶. These findings might lead to the conclusion that self-ligating brackets are less likely to promote microbial adhesion due to the absence of elastomeric rings. It has been postulated, for example, by the manufacturer that due to the smaller size and the absence of the elastomeric rings, SPEED (Strite Industries, Cambridge, Ontario, Canada) brackets accumulate less dental plaque than traditional twin brackets, resulting in fewer signs of gingival inflammation.

Until recently, only a few case reports but no *de novo* plaque formation assays or randomized clinical trials with different orthodontic brackets have been reported^{5,12,27}. In 2007 Van Gastel *et al.* conducted an examiner-blind, split-mouth, randomized clinical trial, and comparatively evaluated the microbiological environment, the clinical periodontal parameters and the crevicular fluid flow between control teeth and teeth bonded with the SPEED self-ligating bracket and a conventional twin bracket (GAC, Central Islip, NY) by means of a *de novo* plaque growth experiment with a duration of 7 days²⁸.

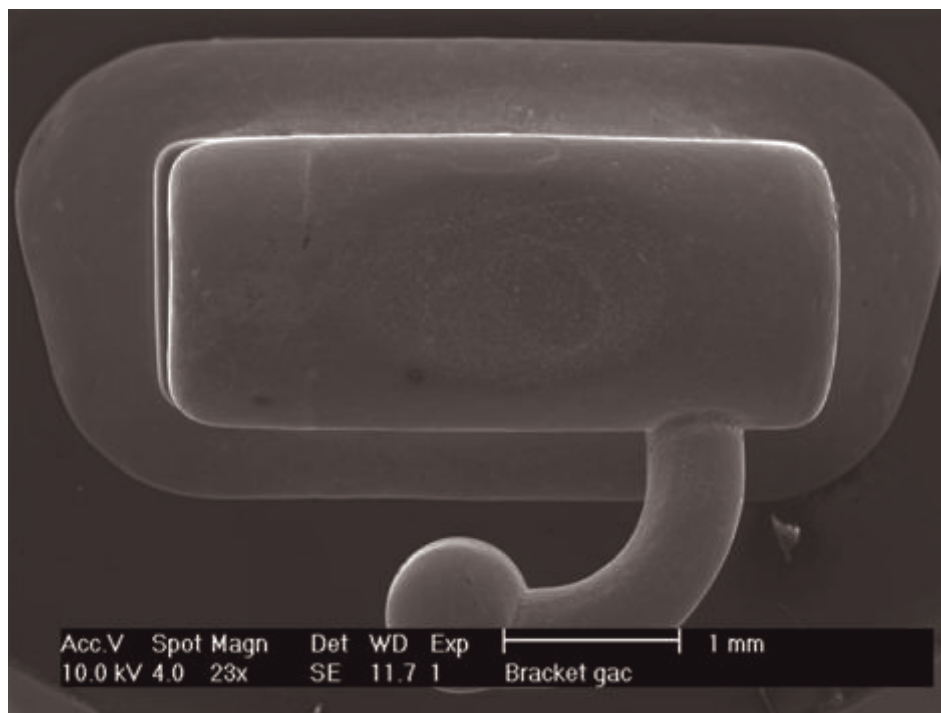
Sixteen dental students participated fulfilling the following inclusion criteria: no smoking, absence of extensive dental restorations or adhesive fixed partial dentures, a sulcus bleeding index²⁹ of less than 0.3 and no antibiotics during or up to 4 months prior to the study. Previous orthodontic treatment with fixed appliances was also recorded, because this might have consequences on the smoothness of the buccal enamel³⁰ and as such on the microbial adhesion in the early formation of the dental plaque

film³¹⁻³³. In every subject the mouth was divided into four quadrants, two of which served as controls. Two types of brackets, SPEED and GAC conventional twin were used (Fig. 11.2). The GAC (G-sites) and SPEED (S-sites) bonded teeth were alternated,

giving rise to four different experimental settings. One possible example of the study design is seen in Fig. 11.3. The teeth bonded with the different brackets were compared with each other and with the non-bonded control sites (Fig. 11.4). The brackets



a



b

Fig. 11.2 Scanning electron microscopic images of the different brackets, the SPEED bracket (a) and the GAC bracket (b).

were bonded 3 mm above the gingival margin, and the involved teeth were stained with erythrosine to verify the baseline conditions since the primer might capture some pigment and give a pink shine after disclosure.

Table 11.1 describes in detail the interventions on the subjects that had taken place per visit. On day 7 the subjects came for the last clinical measurements, the removal of the last brackets and for a

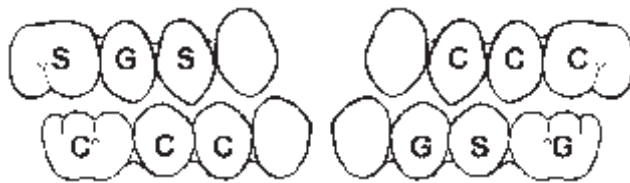


Fig. 11.3 Example of the split-mouth design applied to a single patient. (S-site = tooth bonded with a SPEED bracket; G-site: tooth bonded with a conventional GAC bracket; C = control, non-bonded tooth)

thorough cleaning and polishing of the teeth. At baseline, on day 3 and on day 7 (before and after plaque disclosing) digital color photos were taken in order to follow the undisturbed plaque formation (Figs. 11.4, 11.5 and 11.6). On the same occasions

Table 11.1 Flow chart of the study, with the interventions depicted per contact.

	Intake	Day 0	Day 3	Day 7
Scaling and polishing	x	x		x
Crevicular fluid sampling		x	x	x
Pocket probing depth measuring		x	x	x
Bleeding on probing measuring		x	x	x
Bracket placement		x		
Removal brackets PM1			x	
Removal brackets PM2 and M2				x
Oral hygiene instruction	x	x	x	x



a



b



c



d

Fig. 11.4 Clinical example of the experimental setting on day 1 before (a,b) and after (c,d) plaque disclosure.



Fig. 11.5 Clinical example of the experimental setting on day 3 before (a,b) and after (c,d) plaque disclosure, with SPEED brackets bonded on teeth 14,16 and 35 and GAC brackets on teeth 15, 34 and 36.

the following parameters were scored (on day 3 only the first premolars and on day 7 the remaining teeth): crevicular fluid flow, probing depths and bleeding on probing.

The numbers of aerobic and anaerobic CFU (colony forming units) in supragingival plaque samples from the different sites showed significant material differences. S-sites in general allowed more plaque formation than conventional G-sites. S-sites showed significantly higher CFU aerobes than conventional sites and both bracket sites had higher values than the control sites. The CFU aerobes were significantly higher for all sites on day 7 when compared with day 3. Also for the CFU anaerobes, significant differences between the materials were seen. On day 3, the CFU anaerobes only were significantly higher in the S-sites when compared to control sites, and on day 7, more anaerobic species were seen and both SPEED and conventional sites showed signifi-

cantly higher values than the control sites. It is noteworthy that between SPEED and conventional sites no significant differences for CFU anaerobes were seen either on day 3 or on day 7.

The crevicular fluid volume showed a significant material effect over time. An overall increased crevicular fluid flow from day 3 to day 7 was obvious. On day 3 there was only a significantly higher flow in S-sites compared to control sites, but on day 7 the flow was significantly higher in both bracket sites versus control. The difference between SPEED and conventional sites never reached the level of significance. On day 1 no significant inter-material differences in pocket probing depth (ppd) were present. The increase in probing depth was significantly higher for S-sites compared to GAC sites and control sites. The latter was due to changes at the proximal sites since the mid-buccal sites showed no significant changes. The portion of sites



Fig. 11.6 Clinical example of the experimental setting on day 7 before (a,b) and after (c,d) plaque disclosure, with SPEED brackets bonded on teeth 16 and 35 and GAC brackets on teeth 34 and 36.

bleeding on probing clearly increased over time for all, but inter-site differences were not detected.

The use of dental students with good oral health as subjects for this study is important as several studies indicated an increased plaque accumulation and thereby a different gingival reaction in the presence of gingival inflammation^{34,35}. This increased plaque formation has also been shown in experimental gingivitis studies^{34,36}. As the authors were mostly interested in the early dental plaque formation, the duration of the study was set at 7 days. This was also positive for the compliance of the students as longer periods would have resulted in a reduced cooperation with tooth brushing.

The increased probing depth recorded during this study is most likely caused by gingival enlargement or by deeper penetration of the probe into the weakened junctional epithelium. As these two processes could simultaneously contribute to the increase in

probing depth, a distinction between these processes cannot be made with the instruments used in this study. During the relatively short period of this study, gingivitis was induced, but attachment loss probably did not occur^{11,12}.

The increase in crevicular fluid described above is unlikely to be induced by the procedure of bracket placement alone. Phosphoric acid is widely used as an etching product in both adhesive dentistry and orthodontics but necrotizing effects on periodontal soft tissues have been reported³⁷. White ulcerative lesions were described in cases where the phosphoric acid was accidentally in contact with the mucosa for several minutes³⁸. To avoid these adverse effects in this study, the phosphoric acid was applied locally at a safe distance from the gingival margin with a lightly soaked mini-sponge.

It has been shown dental adhesives are toxic to the gingival fibroblasts *in vitro*³⁹, and particularly

the residual monomers may cause gingival inflammation and irritation⁴⁰. The same gingival contact prevention protocol as used for the phosphoric acid was applied for the bonding material. The bonding material was directly polymerized and thus contact with the gingival margin was prevented. These were the reasons why it was assumed that these two products did not contribute to the inflammatory response seen in this *de novo* plaque growth experiment.

Besides the crevicular flow, the bleeding on probing tendency is another parameter to quantify gingival inflammation and was significantly higher on day 7 compared to baseline for all sites. There were, however, no significant inter-site differences detected on the different days. A possible explanation for the lack of significant inter-material differences was possibly due to the lower discriminative value of this parameter. Comparison of the bonded teeth to the non-bonded control teeth showed a faster undisturbed plaque formation in the bonded sites, two to eight times more CFUs were counted. These results are consistent with some changes in crevicular fluid flow and the periodontal pocket depth measurements. Concerning the crevicular flow, neither on day 3 nor on day 7 were significant differences between the two bracket types seen. But the higher bacterial load and the lower CFU ratio (aerobe/anaerobe) at the S-sites might have resulted in a faster increase in crevicular fluid flow there (Fig. 11.7). The crevicular flow at the S-sites was already significantly higher than the control sites on day 3, whereas the G-sites did not show

higher crevicular flows compared to the control sites earlier than day 7.

A significantly higher crevicular flow in the S-sites versus control sites on day 3 was seen without a significant difference in CFU ratios (aerobe/anaerobe) between these two groups. Nevertheless there was a significant increase in absolute values of both aerobe and anaerobe CFU, which could be the explanation. On day 7, the GAC sites showed significantly higher crevicular flows than the control sites, without a significantly lower CFU ratio (aerobe/anaerobe) and without significantly higher anaerobe CFU.

The fact that the CFU ratio (aerobe/anaerobe) was lower in the control sites than in the GAC sites was another unexpected outcome. A possible explanation is that the dental plaque retrieved from the control sites is mostly formed in strict contact with the gingival margin as well as the interdental space (Figs. 11.5 and 11.6). These two niches are predominantly colonized by anaerobic bacteria. The total amount of bacterial plaque however was higher on GAC sites than on the control teeth. This was expected as the total surface available for plaque adhesion is significantly larger and more irregular at the GAC sites. The natural automatic cleaning of the teeth by food mastication is less efficient in the presence of bonded brackets. The lower CFU ratio (aerobe/anaerobe) as mentioned above was not supported by the crevicular fluid flow which was lower in the control sites. This implies that in this experiment, the CFU ratio (aerobe/anaerobe) alone is not

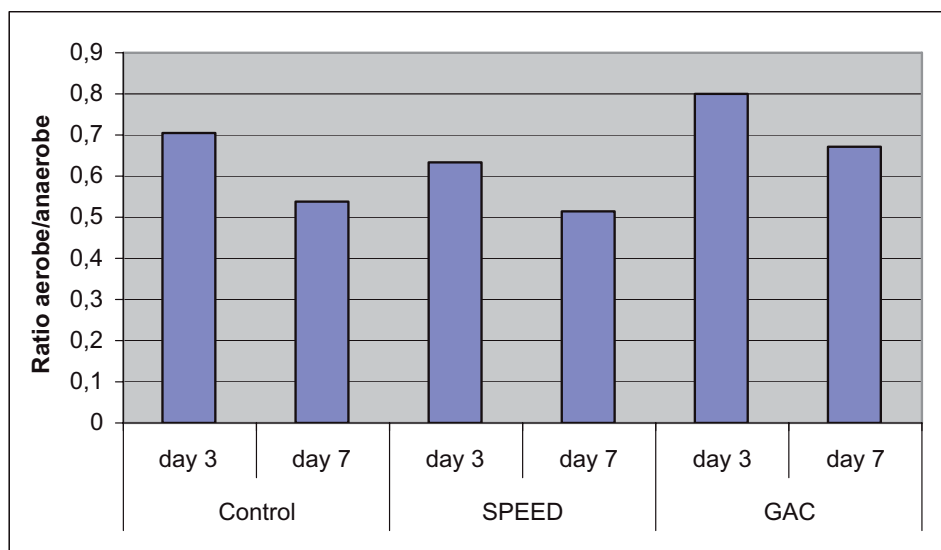


Fig. 11.7 Mean CFU ratio (y-axis) on the different sites depicted per day.

responsible for the development of gingivitis, but the total amount (absolute values) of bacteria is also important.

Significant differences were seen for the increase in pocket depth and CFU aerobes, CFU anaerobes and the CFU ratio (aerobe/anaerobe). The increased CFU counts in the SPEED sites compared to the GAC sites were not expected because of the limited dimensions of the SPEED bracket and the presence of a smooth clip instead of an elastomeric ligature. To find differences in surface characteristics between the two bracket types, scanning electron microscope (SEM) images with several enlargement factors were taken (Fig. 11.2). These qualitative SEM images revealed remarkable irregularities on the interfaces between the different parts of the SPEED attachments (both of the bracket and the tube). These parts seem to be welded together causing an irregular surface, which might have lead to the increased plaque adhesion in the S-sites.

Because randomized controlled trials of this type have not been performed so far, it is not possible to compare our findings to those of other authors. Different orthodontic bracket types have not been compared microbiologically and clinically *in vivo* as of yet. Nevertheless there are indications that placement of orthodontic fixed appliances has an impact on the microbiological characteristics of the dental plaque. Lee *et al.* found significant differences in the prevalence of putative periodontal pathogens in subgingival dental plaque from gingivitis lesions in orthodontic patients. Their study succeeded in detecting significant differences between the subgingival dental plaque of gingivitis lesions in patients with and without orthodontic fixed appliances. *T. forsythia*, *T. denticola* and *P. nigrescens* were significantly more common in the samples obtained from the orthodontic patients than in the samples obtained from the non-orthodontic control patients⁴¹. Their results as well as ours indicate that the local changes associated with the wearing of orthodontic brackets may affect the prevalence of periodontal pathogens in dental plaque. However, no differences in periodontal pocket depth were seen between their groups and no different bracket types were evaluated. Additionally, the orthodontic group might have received more hygiene instructions resulting in better oral hygiene, making the two groups difficult to compare. Huser *et al.* performed clinical and bacterial examinations before the beginning of treatment and after

placement of the orthodontic appliances up to 90 days. Plaque index and bleeding scores increased significantly on banded teeth as compared with control sites, the probing depth however remained within normal limits for both the experimental and the control groups. The composition of dental plaque was only determined by dark-field microscopy and showed significant shifts in the test sites after banding with an increase in the percentage of spirochetes, motile rods, filaments and fusiforms. During the same period no significant changes in the bacterial distribution were observed in the control group⁴². Over a 6-month period, Petti *et al.* performed a similar study where they comparatively evaluated the influence of fixed and removable orthodontic appliances on supra- and subgingival microflora, whilst no periodontal parameters were examined. Their data suggests that in well motivated patients with good oral hygiene, gingivitis and periodontitis did not occur during the first 6 months of treatment. The significant modification of oral microbiota, shown by subjects with fixed appliances, however, is in line with our findings and suggests that the risk for gingivitis in the following months of therapy is still high and the risk for periodontitis cannot be excluded¹⁰.

Comparative studies between bracket systems have not been reported as of yet. Some information about the difference between brackets ligated with elastomeric rings or ligature wires is available^{6,26}. Türkkahraman *et al.*, as reported earlier, showed that teeth ligated with elastomeric rings exhibited a slightly greater number of microorganisms than teeth ligated with steel ligature wires, but with little clinical importance²⁶. No significant effect of archwire ligation method was observed in gingival index, in plaque index and in probing depth of bonded teeth. However, the teeth ligated with elastomeric rings were more prone to bleeding gingivae. The observation period in this research was 5 weeks; maybe more explicit differences would be seen after a longer period of orthodontic treatment. Forsberg *et al.* evaluated microbial colonization of 12 patients treated by fixed orthodontic appliances and reported that the lateral incisor attached to the archwire with an elastomeric ring exhibited a greater number of microorganisms in the plaque than teeth ligated with steel wire⁶. They only analysed the microbial colonization, with much emphasis on the presence of *S. mutans* and did not take the periodontal situation

into account. As discussed above, the ligation method might have an impact on the microbial and clinical periodontal parameters of the bracket-bearing teeth. From this point of view, self-ligating brackets would induce less adverse situations compared to traditional brackets combined with elastomeric rings; however, the existing evidence does not support the notion that self-ligating brackets would present less plaque accumulation and fewer signs of clinical periodontal inflammatory parameters.

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12

Treatment Mechanics with Self-Ligating Brackets

David J. Birnie

INTRODUCTION

Both conceptually and practically, self-ligating brackets have existed since the 1920s. However, the mechanical complexity and fine engineering tolerances required meant that innovative designs suffered from unreliability of the closure mechanism. The first self-ligating bracket that was reliable enough for routine use was the SPEED bracket designed by Dr G. Herbert Hanson in the early 1970s. Both active and passive self-ligation designs followed in the 1980s and 1990s; however, since 2000, the number of self-ligating bracket designs coming on to the market has accelerated dramatically.

If the origins of the self-ligating bracket lay in a desire to simplify the complexity of wire ligation, this advantage was to some extent diminished by the advent of the elastomeric ligature. The elastomeric ligature was, however, in many respects a retrograde step in ligation technology. It often did not achieve full bracket engagement, particularly on displaced teeth, had higher friction than wire ligatures and absorbed oral fluids with time resulting in loss of elastic properties, discoloration, dimensional and color instability and plaque accumulation. However, it was less time consuming to place and remove than wire ligatures and patients liked the ability to customize the appearance of fixed appliances by selecting different colored ligatures.

Early users of self-ligating appliances noticed that tooth movement seemed to be more rapid than with appliances using conventional ligation and this fact, as much as ease of ligation, has driven the development and popularity of self-ligating brackets systems. Full archwire engagement within the bracket slot is an important tenet of treatment with edgewise appliances; self-ligating brackets demonstrate such con-

vincing superiority over conventional ligation in this respect that this feature alone makes a cogent case for considering the supplanting of conventionally ligated brackets with self-ligating brackets.

The principal benefits of self-ligating brackets are:

- Simplicity of archwire entrapment and release
- Full archwire entrapment at all times
- Reduction in sliding friction

This chapter explores how these three factors can affect treatment biomechanics for labial appliances. Self-ligating appliances also exist in lingual fixed appliance systems and for further information on these, the reader is referred to Geron¹. While self-ligating brackets can be used with no change in the orthodontist's usual biomechanics, there is an opportunity to add value to treatment for the patient if the treatment philosophies of the pioneers of self-ligation are practised.

DIAGNOSTIC PHILOSOPHIES

Reasons for tooth extraction

As orthodontic appliance systems have evolved from unsophisticated removable appliances to highly complex and intricate examples of micro-engineering, orthodontic diagnosis has also changed. Tooth extraction is an interesting example. The reasons for permanent tooth extraction in orthodontics are as follows:

- Biomechanical
 - To create space for tooth alignment
 - To permit an increase in overbite
 - To reduce an overjet

- Alteration of facial appearance
 - To prevent an increase in fullness of the lips post-treatment
 - To reduce lip fullness
- Achievement of stability
 - To place teeth in a position that will enhance stability of the post-treatment result
- Pathology
 - Gross caries
 - Periodontal disease
 - Ectopic teeth whose position cannot be orthodontically corrected

Tooth extraction, apart from being something disliked by patients, has potentially several adverse mechanical sequelae for which compensatory mechanics are required:

- Overbite increase
- Lingual tooth inclination
- The need for space closure
- Tipping at extraction sites
- Rotation into extraction sites
- Difficulty in controlling anchorage

Berger² summarizes Dr Hanson's treatment philosophy for the SPEED appliance as follows:

- Try to treat without extractions in all cases which appear to have the necessary potential
- If treatment objectives cannot be accomplished without extractions, extract second bicusps to minimize any tendency toward unattractive reduction in the prominence of the dentition
- Use preliminary functional appliances to favorably alter jaw growth patterns wherever it is desirable and feasible
- Employ intra-oral distalization mechanics instead of headgear when conditions permit
- Expand arches which have failed to develop to their full potential
- Intrude upper anterior teeth in patients who exhibit a lot of gingival tissue
- Correct tooth rotations to ideal alignment without any over-correction and rely upon interproximal reshaping and circumferential supracrestal fiberotomies to enhance retention
- Overcorrect class II or class III buccal segment relationships where a strong relapse tendency is expected

Although Berger attributes the feasibility of this treatment philosophy to the responsiveness of the

SPEED bracket to light forces due to the energy stored in the superelastic nickel–titanium clip during archwire deflection, a substantial contribution to the efficiency of the bracket may come from the fact that the archwire is always entrapped within the bracket slot and the low frictional characteristics of the active self-ligating bracket.

Light forces are thought to be both physiologically and mechanically advantageous. Physiologically, they allow tooth movement to occur with the minimum of force, possibly reducing the risks of root resorption and cortical plate perforation. Mechanically, light forces might be thought to minimize anchorage requirement³ although Southard *et al.*⁴, using a mathematical model, have discounted this suggestion. What actually happens *in vivo* is unresolved and requires further investigation. In addition, light ligation forces might allow the soft tissue forces to contribute to tooth movement, the development of archform or provide anchorage.

These concepts are similar to those advocated by Dr Dwight Damon⁵ for the Damon System appliance, whose treatment philosophy can be summarized as follows:

- Treatment should be planned to optimize facial appearance as maturation and aging occur
- Treat non-extraction where biologically possible and compatible with dental and facial treatment goals
- Use light forces, in an appliance where direct transmission of archwire energy to bracket can be achieved without modification or absorption by ligatures, in order to move teeth with adaptation of the alveolar bone by ensuring the orthodontic forces do not impede blood supply in the periodontium
- Use functional appliances to obtain anteroposterior correction of class II malocclusions
- Do not use rapid palatal expansion appliances or headgear
- Utilize the oral musculature to assist in correction of the malocclusion by:
 - Allowing the orbicularis oris and mentalis muscles to provide a 'lip bumper' effect which minimizes anterior movement of the incisors during non-extraction treatment
 - Expanding the posterior buccal segments with light archwires thus allowing the tongue position to elevate and move forward producing a



Fig. 12.1 Patient RO 34 months after the end of active treatment: uncrowded state.

new force equilibrium between it and the facial muscles

The reality is that it is now rarely necessary to extract teeth simply to gain alignment because of the sophistication of modern self-ligating appliances which allow archwire forces to be transmitted directly to the teeth without modification, modulation or absorption by elastomeric ligatures. This was not true of primitive orthodontic appliances, such as removable appliances or early fixed appliances of half a century ago, where tooth extraction was necessary to provide sufficient space for tooth alignment.

This in turn creates doubt about the definition of crowding which is traditionally conceptualized as a mismatch in size between the teeth aligned in an ideal archform and the capacity of the dentoalveolar bone to accommodate them. Fundamental to this concept is the idea that crowding is a permanent state that can only be alleviated by the extraction of permanent teeth. This being so, the same dental arch should not be able to exist sequentially in the crowded and uncrowded state; however, it is now clear that this is possible (Figs. 12.1, 12.2). It is perhaps time for the orthodontic specialty to reflect on the need for extraction rates in orthodontics which range from 80% to 10%. An audit⁶ in the south of England has identified a steady decrease in extraction rates over the past 5 years from 60% to their current level of 40%; this is not thought to be different to the rest of UK practice. The practice of



Fig. 12.2 Patient RO at the start of treatment: crowded state.

removing healthy body tissue is one which most surgical specialties have discarded; the cohort of adolescent orthodontic patients currently in treatment in developed countries are likely to live into their eighties, nineties and hundreds and may well need the healthy teeth whose removal were prescribed by a well-intentioned orthodontist.

The effect of orthodontic treatment on facial appearance

The effect of orthodontic treatment, and in particular extraction or non-extraction treatment, on facial profile and frontal facial appearance has been debated for a considerable period of time. Most attention has been paid to the effects on the facial profile. Although effects have been claimed for the effects of tooth extraction on frontal facial appearance, they are poorly documented. For facial profile, the following statements vary between being proven and anecdotal:

- Teeth provide support for the upper and lower lips
- The nasolabial angle is of less importance than the drape of the upper lip to a true vertical – labrale superioris should lie anterior to columella to ensure a forward slope to the upper lip for optimum upper lip esthetics
- Substantial tooth proclination can take place with little effect on the facial profile (such as in the correction of class II division II malocclusion).



Fig. 12.3 Patient BB profile at the start of treatment.

These changes may be correlated with modest anterior tooth movement

- The facial profiles of patients with good muscle tone (such as class II division II malocclusions) are less affected by increases in tooth proclination or anterior tooth movement than those with lax musculature
- The effects of non-extraction treatment in relation to increased lip fullness are unpredictable due to the difficulty in:
 - Assessing muscle tone. In Figs. 12.3, 12.4 and 12.5, the profile of a patient is shown together with her upper and lower occlusal views at the start of treatment. The patient had extremely good muscle tone and was treated without extractions. The patient's profile and her upper and lower occlusal views 48 months after the end of active treatment are shown in Figs. 12.6, 12.7 and 12.8. Despite significant arch expansion, there is little change in her facial profile
 - The amount of posterior expansion that may occur – the greater the posterior expansion, the less anterior movement of incisors will occur
- Facial growth and maturation during the teenage years will counteract slight over-fullness of the profile at the end of active orthodontic treatment due to forward projection of the nasal tip and the chin



Fig. 12.4 Patient BB upper occlusal at the start of treatment.



Fig. 12.5 Patient BB lower occlusal at the start of treatment.

- Extractions have a predictable qualitative negative effect on lip fullness if mechanics are designed to optimize tooth retraction and retroclination
- Populations with short apical bases and a tendency to bimaxillary proclination and convex facial profiles will have higher extraction rates than populations with flatter faces (such as southern Chinese populations)

The consequence of these facts, hypotheses and anecdotes is that it is difficult to predict the effect of non-extraction treatment on facial profile until tooth alignment has taken place. Conversely, tooth extraction has a predictable effect on facial profile and therefore extraction decisions designed to reduce the

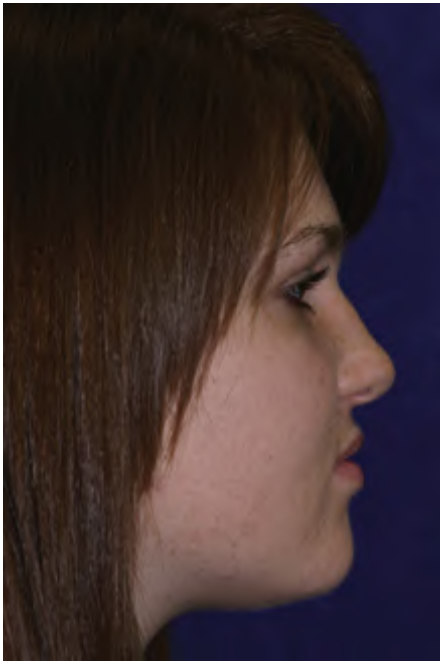


Fig. 12.6 Patient BB profile 48 months after the end of active treatment.



Fig. 12.7 Patient BB upper occlusal 48 months after the end of active treatment.

fullness of the facial profile can be made at the start of treatment.

ASPECTS OF CLINICAL BIOMECHANICS

Types of tooth movement

Charles Tweed described first-, second- and third-order tooth bends as a method of obtaining detailed sequential tooth movement in the finishing stages of



Fig. 12.8 Patient BB lower occlusal 48 months after the end of active treatment.

orthodontic treatment with the edgewise appliance. In general, alignment (first-order correction) was obtained before the correction of angulation (second-order correction), and the achievement of optimum inclination (third-order correction) by the use of torque was one of the final aspects of treatment. Larry Andrews, with the introduction of the straight-wire appliance, added a fourth dimension, that of rotation (for molars) or counter-rotation (for molars, premolars and canines). Counter-rotation counteracted the tendency of a tooth to rotate into the extraction space during space closure in extraction cases and is a consequence of the lack of control manifested by conventionally ligated appliances. Self-ligating appliances have rotation built into molars to correctly position these teeth in relation to the line of the arch; however, counter-rotation is unnecessary and artifactual because of the full entrapment engagement of the archwire within the slot at all times.

Tweed's sequential classification of tooth movement is not only incomplete in that it does not describe all possible tooth movements but the advent of pre-adjusted edgewise appliances and nickel-titanium wires mean that the correction of in-out, rotation, up-down (levelling of individual teeth) and tip may all occur simultaneously in the early stages of treatment. In fact, one of the earliest tooth movements to occur is space opening to allow first-order correction of displaced or rotated teeth so it may be argued that second-order movement occurs before first-order movement. It is therefore time to move forward from Tweed's seminal but dated classification.

It is helpful to divide tooth movement into the movement of individual teeth and the movement of segments of teeth (or several teeth together). Although the description of the tooth movement is the same for both, the biomechanics used to produce the tooth movements are different; for example, the biomechanics used to produce intrusion of a single tooth are different to those designed to effect overbite reduction.

Individual tooth movement

The movement of an individual tooth can be described by a combination of six parameters. Looking at a tooth from its labial or buccal surface, consider the occlusal plane to represent the x-axis, a vertical line perpendicular to the occlusal plane running up through the clinical crown to represent the y-axis and a z-axis running bucco-lingually at right angles to the other two axes. The tooth can move bodily along, or rotate about, the:

- X-axis
- Y-axis
- Z-axis

The tooth can do any one of these movements singly or all six in combination. The rotation movements are aligned axially rather than radially in relation to each axis. These tooth movements can be mapped to contemporary nomenclature and Tweed's classification of tooth movements as shown in Table 12.1. The translatory movements are represented in Fig. 12.9 and the rotatory movements in Fig. 12.10.

Table 12.1 The mapping of individual translatory and axial momentary tooth movements to Tweed's terminology of tooth movement.

Axis	Orders of tooth movement	Translation	Rotation
X-axis	Second order	Space opening Space closure	Angulation
Z-axis	First order	Buccal or labial movement Lingual or palatal movement	Rotation/ derotation
Y-axis	Third order	Intrusion Extrusion	Inclination

Movement of multiple teeth

The above classification of tooth movement works well for individual teeth but is less satisfactory for the movement of several teeth at the same time. These can again be classified as follows by using an x-, y- and z-axis system:

- Movement of teeth around the arch perimeter – space opening and space closure
- Transverse movement – arch expansion or contraction
- Anteroposterior movement – correction of a class II or class III buccal segment relationship
- Vertical tooth movement – intrusion or extrusion of anterior or posterior tooth segments

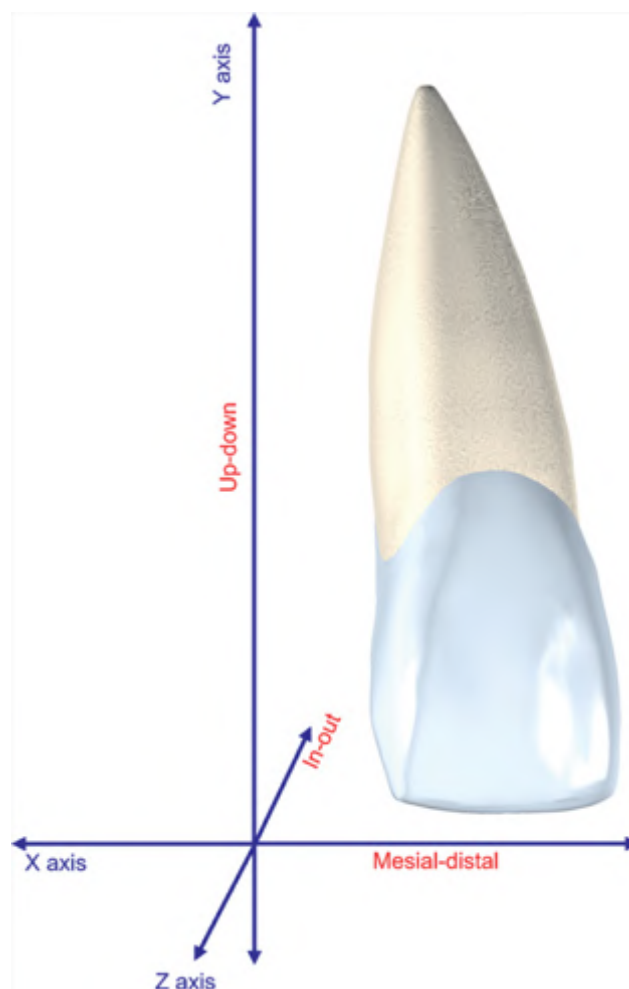


Fig. 12.9 Tooth movement can be defined as translatory movement along the x-, y- and z-axes.

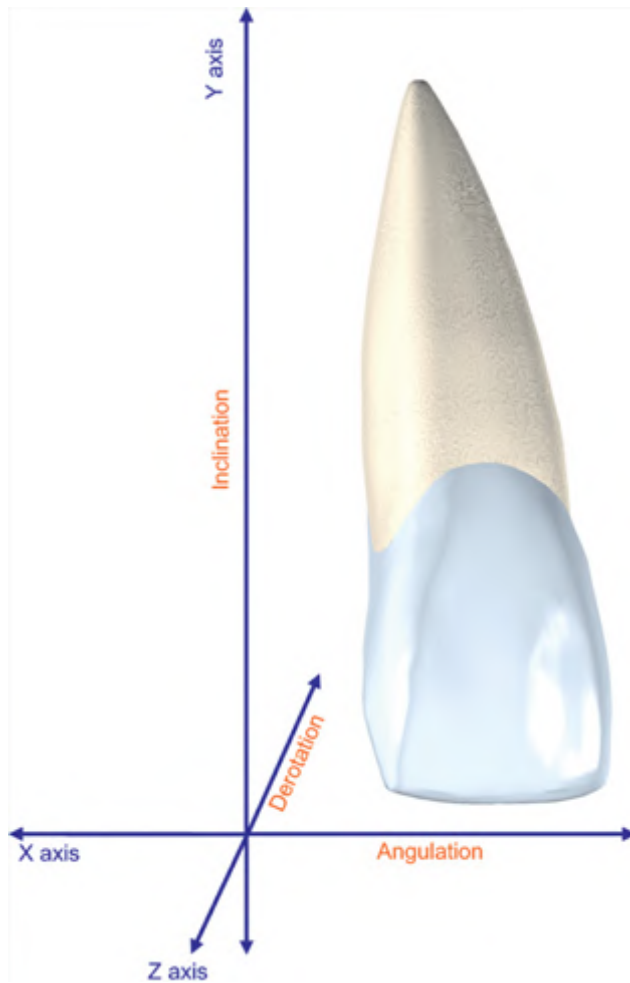


Fig. 12.10 Tooth movement can be defined as rotatory movement along the x-, y- and z-axes.

Fully bonded appliances

The migration from banded to fully bonded appliances has facilitated the fitting of fixed appliances which can now be placed in a single visit of less than 60 minutes. Since many self-ligating systems minimize or eliminate the need for intraoral auxiliaries, molar bands are not required thus reducing cost and inventory and the time and visits taken to fit fixed appliances. It is essential to routinely incorporate all erupted teeth into the fixed appliance. Several systems (3M Unitek SmartClip (3M Unitek, 3M Corporate Headquarters, 3M Center, St Paul, MN 55144-1000, USA), Ormco Damon System (Ormco Corporation, 1717 West Collins, Orange, CA 92867, USA)) have developed self-ligating molar tubes which make the placement of working archwires

extending to the second molars and the placement of archwire-borne fixed class II correctors, such as the TP Flip-Lock Herbst (TP Orthodontics, Inc., 100 Center Plaza, La Porte, IN 46350, USA), much easier. Partially erupted second molars can be bonded with mini-tubes that are bonded to the mesial cusp only.

Hooks

Brackets and molar tubes can have integral hooks or auxiliary slots in the bracket body than can accept a drop in hook or other type of auxiliary. The Damon 3MX, the GAC In-Ovation R and the Strite Industries SPEED bracket are some of those brackets that have auxiliary slots. The Ultradent Opal (Opal Orthodontics, Ultradent Products, Inc., 505. 10200 S., South Jordan, UT 84095, USA) bracket is unusual in that it had an auxiliary archwire slot. Drop-in hooks are useful for guiding elastics (as in center-line correction *qv*) or for developing interdigitation. Caution should be used when using drop-in hooks for class II or class III traction as inadvertent opening of the self-ligating bracket will lead to a loss of tooth control; it is preferable to use archwire hooks for class II or class III traction.

Interbracket span

Interbracket span is a crucial aspect of biomechanics, particularly where it is very short, as when there are severely displaced teeth, or when it is too long, such as across extraction spaces, in the presence of unbonded deciduous teeth or between first and second molar tubes. The significance of interbracket span is a combination of physical distance and archwire stiffness, i.e. interbracket span between first and second molars is an issue with small diameter (0.013" or 0.014" nickel-titanium) initial archwires but not when large diameter round or rectangular archwires are used.

Normal interbracket span is from 3–4 mm (between lower incisors) to 8–9 mm (between central and lateral incisors and between first and second molars). Short interbracket span is most commonly a problem at the start of treatment where it is necessary to engage significantly displaced teeth and this may reduce the interbracket span to below 3 mm if a conventional bracket is used. The solution to this

problem is to use a traction hook as described in *x-axis movement*.

Interbracket spans are a problem between first and second molars, particularly in the lower arch, with 0.013" or 0.014" archwires and it is recommended that second molars are not normally engaged until nickel–titanium rectangular wires are placed – the exception is when the first or second molar is so displaced that it would not be possible to engage a larger sized archwire. However, this circumstance is very rare. Although the interbracket span between upper central incisor and lateral incisor is similar, this is rarely a problem, partly because this area of the mouth is less susceptible to masticatory forces and because the archwire is supported on either side.

Longer interbracket spans can occur when deciduous teeth are present; when this occurs, the use of a broader traction hook (Fig. 12.11) provides support to the archwire and some control of the deciduous tooth without the risk of accelerating root resorption of the deciduous roots as a result of excessive force. Where extraction spaces are present, sheathing the archwire with some soft stainless steel tube can provide the necessary support.

It is difficult to control the terminal tooth on the appliance because it is not controlled from either side but only from the mesial. It is sensible therefore to apply traction to the penultimate tooth to prevent unwanted rotations of the most distal tooth in the appliance.



Fig. 12.11 Thick traction hooks are used on deciduous teeth to support a 0.014" × 0.025" archwire derotating the upper left central incisor.

Friction

While considerable debate exists about the relative advantages and disadvantages of active and passive clips in the clinical scenario, both clip closure designs work satisfactorily in clinical practice. *In vitro* tests show passive self-ligation to have lower resistance to sliding than active self-ligating appliances, although this advantage diminishes once binding between archwire and bracket occurs. In the mouth, the situation is much more complex and frictional resistance and bracket archwire interaction varies continuously; simplistic models, such as that suggested by Southard *et al.*⁴, are probably of limited application. Put simply, tooth (or any other) movement is facilitated by having as little frictional resistance as possible at all times; if it is desired to stop movement, then frictional resistance should be increased.

All tooth movement, with the possible exception of small changes in inclination, require relative movement between bracket and archwire – hence the importance of reducing friction to a minimum while retaining adequate control of tooth position.

Disclusion and equilibration

Just as friction between archwire and bracket can hinder tooth movement, so can intercuspation. There is a strong feeling among some proponents of self-ligating brackets that disclusion or equilibration are techniques that can facilitate both the tooth movement itself and the speed of tooth movement. The technique of disclusion is not new, being used routinely for the correction of anterior crossbites with removable appliances. Disclusion is defined as a separation of the occlusal surfaces of the teeth by placing an obstruction in the interocclusal space that one or two teeth occlude on. Alignment, crossbite correction and overjet correction may all be facilitated by disclusion. Disclusion can be achieved by using bite turbos or bite ramps placed anteriorly behind the upper incisors or by composite pads placed on the molars. The choice of site depends on the type of tooth movement required. These can either be made from composite, using devices such as MiniMolds (Ortho Arch Company Inc., 1185 Tower Road, Schaumburg, IL 60173, USA), or purchased in different sizes (Opal Orthodontics, Ultra-



Fig. 12.12 Equilibration of the upper first molars and bicuspid to facilitate crossbite correction. (Photograph courtesy of Dr Dwight Damon)

dent Products, Inc., 505. 10200 S., South Jordan, UT 84095, USA) to accommodate various sizes of overjet.

Equilibration is the provision of a balanced, smooth occlusal plane by the addition and subsequent adjustment of adhesive to the occlusal surfaces of the posterior teeth as shown in Fig. 12.12.

Disclusion is preferred to equilibration as it:

- Is simpler
- Gives less frictional contact between the teeth

Equilibration may be required when the occlusion prevents the use of disclusion, e.g. when posterior crossbite correction is required and there is a reduced overbite which makes the use of a bite turbo or bite ramp impossible, or in cases with reduced periodontal support⁷. Quantification of the benefits of both disclusion and equilibration are required.

Archwire placement

Archwire placement takes a shorter time with some self-ligating brackets than with conventional brackets. Several studies have demonstrated this including Berger and Byloff⁸ who studied the SPEED bracket, Harradine⁹, who found a saving of 24 seconds per arch for the removal and placement of archwires comparing Damon SL brackets with conventional ligation and Turnbull and Birnie¹⁰ who compared

Damon2 brackets with conventional ligation and found a 76.8 second saving per arch. This latter finding represents a 12.8% time saving on a 20 minute adjustment visit in which both archwires were changed. This study also sub-categorized by material type and size of archwire and demonstrated that the difference in time for archwire placement became more significant for larger archwire sizes in favor of the self-ligating bracket.

Later generations of self-ligating brackets have become much easier to open and close with many closing simply with finger pressure. Opening requires an easy to use tool. It might be expected that if the studies above were repeated, then the current generation of self-ligating brackets would show greater time savings.

Archwire location

One of the advantages of self-ligating brackets is their reduction in friction over conventionally ligated brackets. However, this reduction in frictional resistance brings problems. Whereas conventionally ligated brackets have sufficient frictional resistance from elastomeric ligatures to prevent the archwire swivelling from left or right, self-ligating brackets, like the Begg appliance, have such low friction that unless counter-measures are taken to positively locate the archwire and prevent it moving through the brackets, it becomes a significant cause of unscheduled visits. Even a very small projection of the archwire through the terminal tube can cause significant discomfort so two stops are usually required to provide positive archwire location. The techniques available are:

- The use of crimpable soft stainless steel stops. These are the most popular technique and many archwires come with stops already in place. These stops can be placed distal to canines to maintain consolidation of the labial segments (Fig. 12.13), or mesial to second molars in first molar extraction cases to prevent mesial movement of these teeth while anterior alignment takes place
- The use of composite stops. These are not as effective as stainless steel stops as they do not grip the archwire as well as soft stainless steel stops
 - Where stops are used, it is suggested that these are placed in the upper right premolar region in the upper arch and in the midline in the lower



Fig. 12.13 The soft stainless steel stops on the lower archwire have been placed distal to the lower canines to prevent space opening up in the lower anterior segment. In the upper arch, the stops have been placed mesially and distally in the first bicuspid–cuspid interbracket space. Crimp-on hooks are being used to locate posterior V elastics to close down the lateral open bites.

arch. Where crowding exists, these stops should be placed as far away from the crowding as possible

- Archwire bends. Bends placed in the archwire will prevent swivelling so long as they are sufficiently large not to slide into the bracket and are placed close enough to the brackets to prevent swivelling; two bends are usually required. A particular case of these are dimpled archwires provided by manufacturers. These are provided where reverse curve nickel–titanium or titanium–molybdenum archwires are used although strictly are only necessary when the archwire is non-formable. The size of the dimple is rarely exact enough to prevent all lateral movement of the archwire without which the patient may feel discomfort from the archwire ends. The dimples can work their way into the slot and cause undesirable changes in angulation or inclination and so are a special rather than a universal solution
- Presoldered posted (preposted) or crimpable archwire hooks. Only possible when working archwires are used, preposted archwires are the most effective way of localizing the stainless archwires particularly when elastics or fixed class II correctors are used. Crimpable hooks are a more expensive and less secure method of attaching hooks to the archwire and should only be used when it is not possible to use preposted archwire because:

- Hooks cannot be soldered to the archwire, e.g. when titanium–molybdenum archwires are used
- The desired archwire size is not manufactured with preposted hooks
- The distance between the presoldered posts does match the available interbracket space

Archform

The recommended archform varies from appliance to appliance. However, the literature on archform is fairly sparse and even sparser on self-ligating appliances and archform. There is evidence that non-extraction cases finish treatment with broader arches than extraction cases¹¹ and that this change is sustained postretention¹².

Of all the self-ligating systems, more has been written about the Damon System appliance archform than any other; it is worth noting that the Damon System has a particularly broad archform. The influence of archwire archform on dental archform is unknown; if the same archwire archform is put in different patients, then the resulting dental archform is likely to be different. One of the characteristics of the Damon System appliance is substantial expansion of the interpremolar and intermolar widths and this is attributed to:

- The width of the archwire archform
- The low friction between archwire and bracket
- The influence of the muscles of the tongue although there is no evidence to support this claim which requires substantiation

Damon⁵ has explained that the archwires used in phases 1 and 2 (see below) develop a dental archform molded by the muscles of the face and tongue, the bone and soft tissue and this is therefore unique to each patient rather than being predetermined.

Periodontal health

One of the concerns about reducing the percentage of extractions is that periodontal health may be adversely affected. In fact, the converse is frequently the case as shown in Figs. 12.14, 12.15 and 12.16. Mavreas⁷ suggests that passive self-ligating appliances, in conjunction with low force small diameter



Fig. 12.14 Patient ZF. This patient showed severe lower incisor crowding at the start of treatment.



Fig. 12.16 Patient ZF. Three years after the end of active orthodontic treatment, the gingival architecture around the lower incisors is normal.



Fig. 12.15 Patient ZF. During non-extraction orthodontic treatment, the lower right central incisor began to show some labial recession.

nickel–titanium archwires and long visit intervals, produce less necrosis and subsequent hyalinization and indirect resorption resulting in favorable periodontal reactions in patients with previous bone loss. This, however, is described in a case report and further evidence is required before this suggestion can be extrapolated. A discussion of this issue from the molecular biology perspective is included in Chapter 5. Much more research needs to be done on this aspect of clinical biomechanics so that the effects of low force non-extraction treatment on oral health are more completely understood.

ARCHWIRE SEQUENCING WITH SELF-LIGATING BRACKETS

Although there is significant variation between the recommended archwire sequences for the various self-ligating bracket systems, a clear pattern is discernible. Treatment can be divided into the following four phases:

- Alignment
- Transition
- Working
- Finishing

Phase 1: alignment

Alignment is achieved with light round wires. Most systems (including 3M Unitek SmartClip, American Orthodontics Time 2 (American Orthodontics, 1714 Cambridge Avenue, PO Box 1048, Sheboygan, WI 53082-1048, USA), Ormco Damon System and Strite Industries SPEED) advocate the use of 0.014" nickel–titanium or copper–nickel–titanium archwires with 0.012", 0.013" or 0.016" of the same materials being possible alternatives depending on the amount of tooth irregularity. The SPEED system also suggests the use of Supercable (Strite Industries Ltd, 298 Shepherd Avenue, Cambridge, Ontario, N3C 1V1, Canada), a seven-strand coaxial super elastic nickel–titanium archwire, which Strite Industries claims delivers 20% of the force of an equiva-

lently sized nickel–titanium archwire and 33% of the force of the same sized stainless steel coaxial archwire². Supercable is available in 0.016", 0.018" and 0.020" preformed arches.

An exception to this initial use of round archwires is GAC's In-Ovation R self-ligating bracket system (Dentsply GAC International, Bohemia, NY 11716, USA). Alpern¹³ recommends an ion implanted GAC Bioforce initial archwire of 0.018" × 0.018" dimensions although a 0.016" × 0.016" archwire of the same material is placed if there is significant irregularity or crowding.

In this first stage of treatment, the aims are to produce tooth alignment with substantial correction of rotations, commence arch levelling and start the development of the final archform.

Time intervals between visits in phase 1

Most individual tooth movement takes place at the start of treatment when teeth are most irregular. In the early stages of treatment therefore, time intervals between visits can be longer as the long range of action of nickel–titanium wires, combined with the secure ligation provided by self-ligation systems, allow progressive controlled tooth movement to occur without frequent supervision. The time interval between visits at this stage can be approximately 10 weeks. Most malocclusions will be ready for phase 2 after 10 weeks but more severe irregularity will take longer; the key principle in this stage is to take as long as the teeth need to gain alignment with small diameter round wires. The moments developed by self-ligating brackets are higher than those for conventional elastomerically ligated brackets¹⁴ and the archwire progression should therefore be slower.

Pain and discomfort in phase 1

One of the more controversial claims for the Damon system has been that it produces less discomfort in the early stages of treatment than conventional elastomerically ligated appliances¹⁵. Miles *et al.*¹⁶ found that in the first few days after appliance placement, patients with the Damon2 appliance reported less discomfort than patients with the 3M Unitek Victory MBT appliance using a qualitative assessment of the presence of pain. A 0.014" copper–nickel–titanium

archwire was used as the initial archwire. However, at 10 weeks, substantially more patients reported discomfort with the Damon2 bracket when engaging an 0.016" × 0.025" copper–nickel–titanium archwire. His conclusions were that initially the Damon2 bracket was less painful, but it was substantially more painful when placing the second archwire. The archwire sequence of 0.014" copper–nickel–titanium initial wire followed by a 0.016" × 0.025" copper–nickel–titanium second archwire ceased to be recommended for the Damon self-ligating appliance in 2003 as it was too large an increase in stiffness and was replaced with a sequence of 0.014" and 0.014" × 0.025" copper–nickel–titanium wires. The increased discomfort may also reflect the greater efficiency of the self-ligating appliance in achieving archwire entrapment and thus increased force application to the teeth resulting in increased discomfort. In a randomized controlled trial with the Damon3 appliance and conventional twin appliance, Pringle *et al.*¹⁷ have demonstrated that patients in the self-ligating group experienced less mean maximum pain intensity and statistically significantly lower mean pain intensity than patients in the conventional twin group. This is not, however, in agreement with the findings of Scott *et al.*¹⁸ who found no difference in the discomfort experienced in the first week after initial archwire placement in a randomized controlled trial using the Damon3 appliance and theOrmco Synthesis appliance, a conventionally ligated pre-adjusted edgewise appliance.

Phase 2: transition, leveling or rectangular nickel–titanium archwires

This phase is variously named according to the self-ligating system being used. In most systems, however, this phase allows the transition from round nickel–titanium archwires to stainless steel rectangular archwires through the use of rectangular nickel–titanium archwires. These archwires range in dimensions from 0.014" × 0.025" to 0.020" × 0.025" depending on the size of the bracket slot (0.018" or 0.022") and the self-ligating system being used.

This second phase of treatment completes alignment and resolves remaining rotations, initiates torque control and continues leveling and archform development.

Time intervals between visits in phase 2

In phase 2, much of the alignment has taken place and the time interval between visits can be therefore be reduced. Normally two sizes of rectangular nickel–titanium archwires are necessary; the first size should be left in place for approximately 8 weeks and the second for approximately 4 weeks.

Phase 3: working archwires

The third phase of treatment uses stainless steel archwires to provide the stiffness required for sliding mechanics. The commonest type of archwire used is 0.019" × 0.025" stainless steel in 0.022" slot brackets and 0.017" × 0.025" stainless steel for 0.018" brackets. It is suggested that preposted wires are used which both provide hooks for interarch elastics and prevent swiveling.

Two interesting variations occur in SPEED and In-Ovation self-ligating systems respectively. The SPEED self-ligating system uses Hills dual dimension archwires for the working archwires; these archwires are rectangular in the anterior section and round in the posterior section. Thus they are available in 0.018" × 0.018" × 0.018" for 0.018" slots and 0.021" × 0.021" × 0.021" for 0.022" slots.

Self-ligating bracket systems with an active clip often have an indent to prevent labial displacement of the clip when closed with consequent loss of archwire control. The effect of this indent is to reduce the depth of the slot on one side of the slot. For example, in an In-Ovation R bracket with a 0.022" slot, the gingival wall of the orthodontic slot is 0.0185" long and the vertical wall is 0.022". The occlusal or incisal wall of the bracket slot is longer at 0.0255". Monacell¹⁹ has suggested using a 0.022" × 0.018" GAC BioForce archwire in a ribbon arch configuration. This fills the 0.022" slot completely yet potentially does not touch the active clip when bracket and archwire are perfectly aligned.

Where the diagnostic philosophy predominantly favors a non-extraction approach to treatment, the rigidity of a 0.019" × 0.025" stainless steel wire, so useful when closing extraction spaces, is less necessary and a few cases will finish at the end of the transition archwire sequence. Cases that principally require detailing can omit phase 3 and go straight to phase 4 with formable TMA archwires to provide the necessary tooth movements.

Time intervals between visits in phase 3

This phase of treatment is when the principal movement of multiple teeth takes place. It therefore is the longest phase of treatment and takes from 20–40 weeks. Patients should be seen at approximately 8 week intervals during this phase. Where interarch elastics are worn well, tooth movement may be rapid and the time interval between visits should be reduced to 4 weeks to ensure over-correction does not take place.

Phase 4: finishing

Careful bracket prescription selection and bracket positioning should minimize the need for archwire bends at the end of treatment. Finishing, however, often requires formable archwires to finalize tooth position. This may include adjusting in–out, angulation, inclination and interdigitation. Titanium–molybdenum alloys (TMA) provide the necessary formability and resilience for this stage of treatment. It is important to maintain an adequate archwire size to maintain tooth position; 0.019" × 0.025" wires are ideal for 0.022" slots. Partial debonding or the use of round wires is not recommended for this stage of treatment because of the potential lack of control of final tooth position that may occur.

Time intervals between visits in phase 4

Phase 4 is of variable length and often quite short – careful attention to the aspects of finishing earlier in treatment will result in a shorter phase 4. This phase may take 10–20 weeks with appointment intervals of between 4 and 6 weeks.

TOOTH MOVEMENT

Bracket selection and positioning to facilitate biomechanics

Bracket prescription

Many self-ligating bracket systems offer different bracket prescriptions to suit different malocclusions. Although prescriptions include prominence, angulation, inclination and rotation, many of the differ-

ences between prescriptions reflect the amount of inclination built into the brackets. All brackets which develop lingual or palatal crown inclination are low torque and all brackets which develop lingual or palatal root inclination are high torque. Prescriptions may be eponymous, such as Damon, Hanson, MBT or Roth, or reflect the relative amounts of inclination built into the bracket; thus upper incisors, for which most variation in prescription exists, come as ultra low (upper central incisors 7°), low (upper central incisors 12°), medium or standard (upper central incisors 17°) and high variations (upper central incisors 22°). The inclination in canine brackets is normally 0° or -7° . Several prescriptions have $+7^\circ$ canine brackets. Typical optional torque values for the Damon System and the SPEED System are given in Tables 12.2 and 12.3.

The following guide to torque selection is given and is derived from Damon and Bagden²⁰ and Weinberger²¹. Low torque prescriptions are used for malocclusions:

- With proclined or palatally positioned upper incisors or palatally impacted canines
- Where extensive use of class III traction, facemask or anterior positioning of the maxillary segment to discourage proclination is required
- With crowding and anterior open bites
- Gaining arch length with upright incisors
- In non-extraction cases with moderate to more pronounced crowding
- When class II mechanics or anterior positioning appliances are used such as the MARA (jointly developed by Dr Douglas Toll in Germany and Dr Jim Eckhart in the USA) as described by Allen-Noble²², the Forsus (3M Unitek, 3M Corporate Headquarters, 3M Center, St Paul, MN 55144-1000, USA) or the TP Flip-Lock Herbst appliances
- In lip bumper cases

The medium or standard torque prescriptions are used for malocclusions:

Table 12.2 Optional torque values in the Damon System.

Upper arch							
	U1	U2	U3	U4	U5	U6	U7
High torque	$+17^\circ$	$+10^\circ$	$+7^\circ$				
Standard torque	$+12^\circ$	$+8^\circ$	0°	-7°	-7°	-18°	-27°
Low torque	$+7^\circ$	$+3^\circ$					
Lower arch							
	L1	L2	L3	L4	L5	L6	L7
High torque			$+7^\circ$				
Standard torque	-1°	-1°	0°	-12°	-17°	-28°	-10°
Low torque	-6°	-6°					

Table 12.3 Optional torque values in the SPEED System.

Upper arch							
	U1	U2	U3	U4	U5	U6	U7
Hanson	$+12^\circ$	$+8^\circ$	-7°	-7°	-7°	-10°	-10°
High torque (Bioprogressive)	$+22^\circ$	$+14^\circ$	$+7^\circ$	-7°	-7°	-10°	-10°
Medium torque (MBT)	$+17^\circ$	$+10^\circ$	-7°	-7°	-7°	-10°	-10°
Regular torque (Roth)	$+12^\circ$	$+8^\circ$	2°	-7°	-7°	-10°	-10°
Lower arch							
	L1	L2	L3	L4	L5	L6	L7
Hanson	$+5^\circ$	$+3^\circ$	-4°	-4°	-8°	-24°	-28°
High torque (Bioprogressive)	-1°	-1°	$+7^\circ$	-11°	-17°	-24°	-28°
Medium torque (MBT)	-6°	-6°	-7°	-11°	-17°	-24°	-10°
Regular torque (Roth)	-1°	-1°	-7°	-11°	-17°	-24°	-28°

- With mild to moderate crowding or space closure
- Where little change is required in incisor or canine inclination
- Where limited space closure is required

High torque prescriptions are used for malocclusions:

- With class II division II incisor relationships
- Where extensive class II traction is required
- Extraction cases with incisor retraction
- Mandibular arch lower incisor extraction cases
- Labially impacted maxillary cuspids, uprighting palatally or lingually inclined canines and first premolar extraction cases
- Decompensation of lower incisors in surgical cases

It is important to remember that in most cases, malocclusions will require a mixture of torque combinations chosen according to the position of individual teeth.

Bracket positioning

Brackets may be positioned to facilitate the desired types of tooth movement. Careful bracket positioning minimizes the time required for finishing and so careful and accurate bracket positioning at the start of treatment is essential. With conventional direct bonding the orthodontist has to estimate the effects of bracket positioning on final tooth position. The introduction of precision bracket positioning/indirect bonding systems, such as OrthoCad's IQ (Cadent, Inc., 640 Gotham Parkway Carlstadt, NJ 07072-2405, USA) andOrmco's Insignia system, allows the final effects of bracket position to be visualized using computer software. It is anticipated that the use of this type of technique will improve finishing and therefore possibly shorten treatment times (Figs. 12.17, 12.18, 12.19 and 12.20).

Brackets and tubes are normally placed on the facial axis (FA) point and aligned with the facial axis of the clinical crown (FACC) as described by Andrews²³. However, this does not always result in

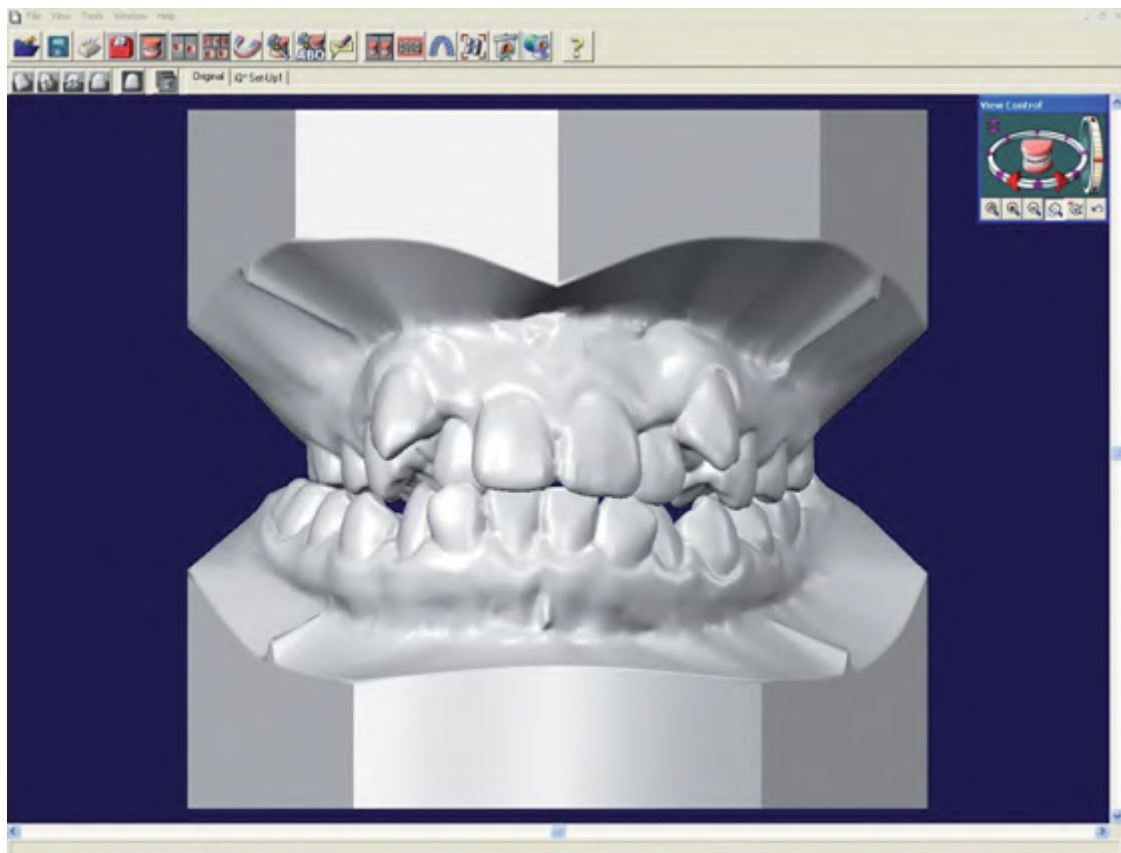


Fig. 12.17 Digital study model of starting malocclusion. (Photograph courtesy of OrthoCAD)

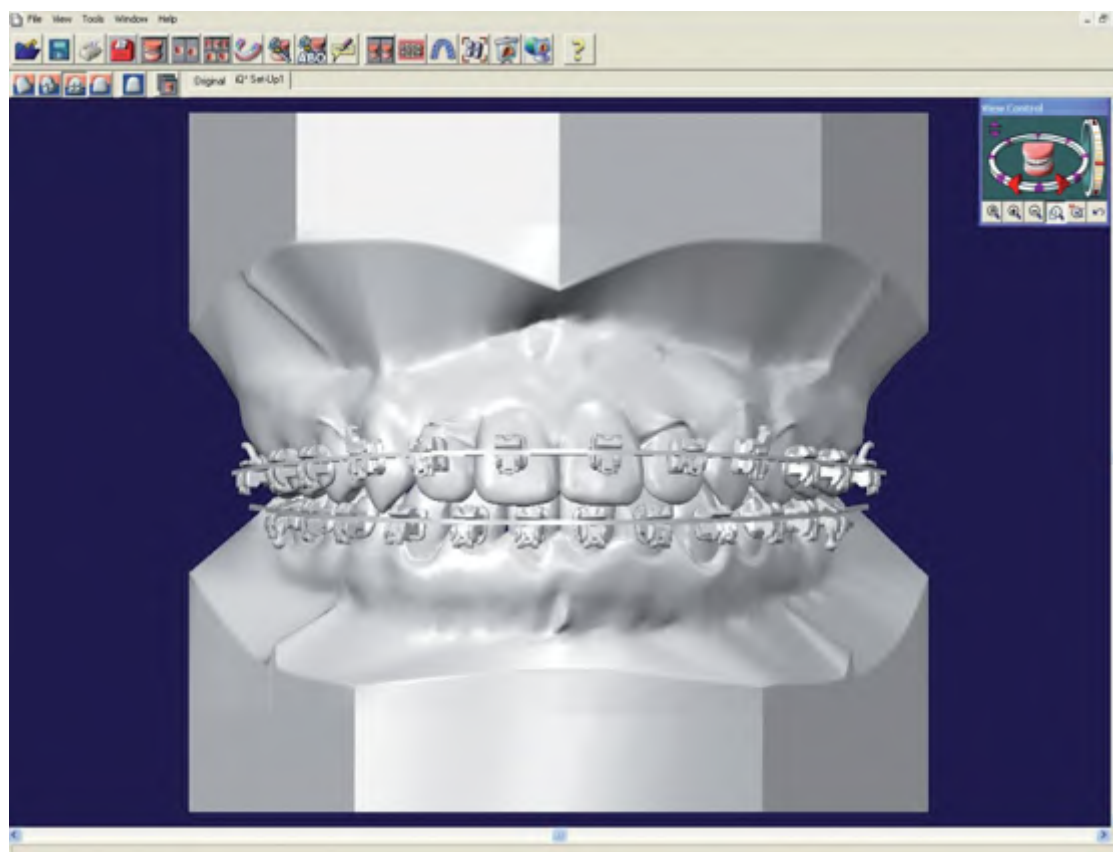


Fig. 12.18 Digital study model of simulated final malocclusion with brackets in place. (Photograph courtesy of OrthoCAD)

the desired tooth positions; in particular, checks should be made to ensure that the marginal ridges are level in the buccal segments. Tooth morphology or appliance design may mean some variations from the method described by Andrews are required, e.g. on lower canines, it is advantageous to position the brackets 0.5 mm anterior to the FACC to ensure correct alignment between canine cusp and the incisal edge of the lower lateral incisor.

Where large translatable tooth movements are required, or where there is a large interbracket span, it may be necessary to exaggerate the angulation of the bracket to make sure adequate root movement occurs such as when opening space for a subsequent implant to ensure adequate divergence of the roots of the teeth adjacent to the implant space, or where a transposition is being corrected.

Where overbite correction is a major part of managing the malocclusion, consider placing the brackets on the incisors and canines more incisal for deep bite cases and more gingival for open bite cases.

Movements of individual teeth

X-axis movement

X-axis tooth movement is space opening (translation) or correction of angulation (rotation); it might be argued therefore that in Tweed's classification this is second-order tooth movement. One of the initial aims of treatment for all crowded malocclusions is to make space for the displaced teeth either by movement of teeth into extraction spaces or by increasing the arch perimeter. Where teeth are excluded from the arch with little or no space to accommodate them, then space needs to be created for them first. This is one of the most important principles of clinical biomechanics for self-ligating bracket systems because most teeth improve in position or erupt spontaneously when space is made for them²⁴.

When teeth have to translate a long distance, such as in transposition cases, consider over-angulating the bracket to ensure that the roots end up in the

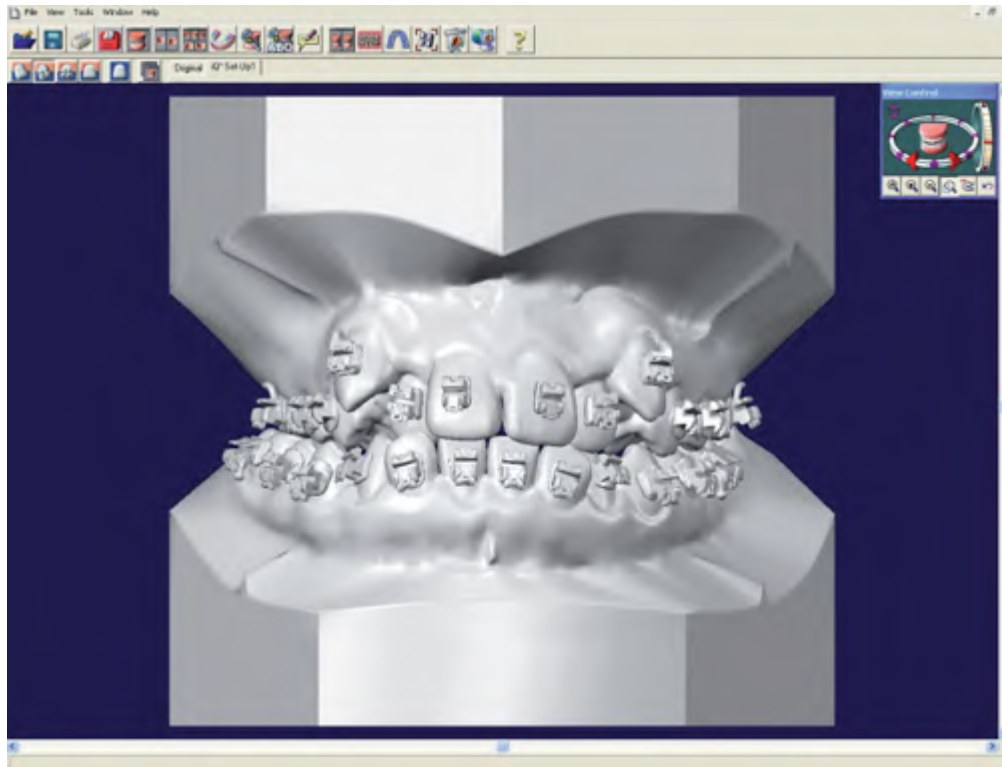


Fig. 12.19 Digital study model of starting malocclusion with brackets in place. (Photograph courtesy of OrthoCAD)

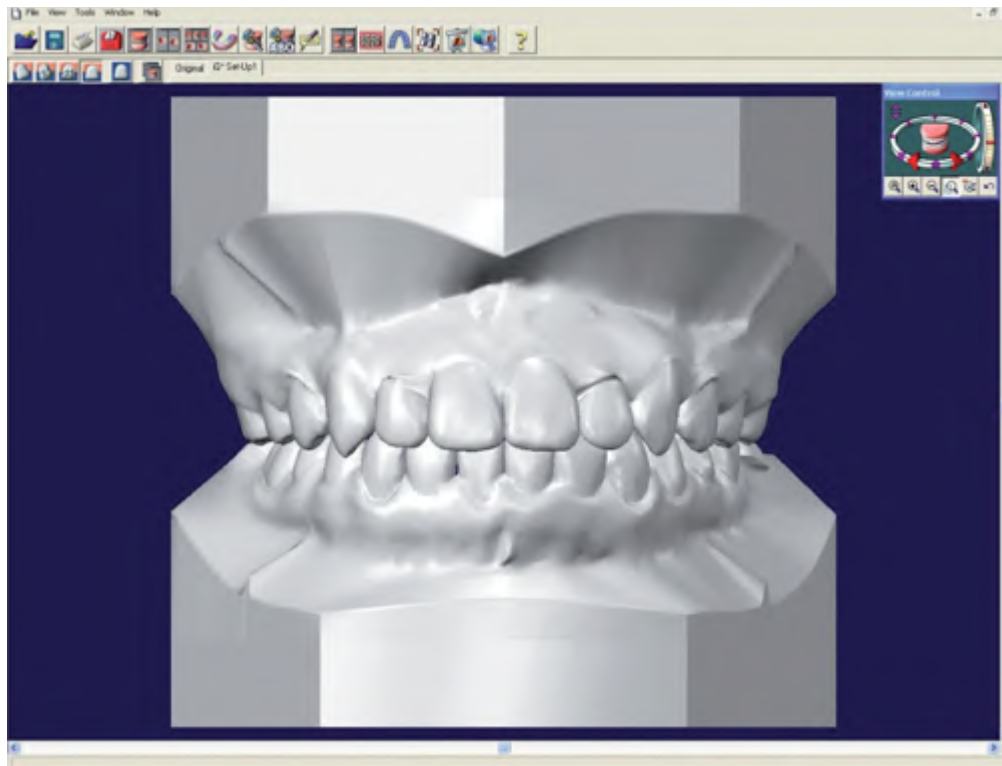


Fig. 12.20 Digital study model of finished occlusion after treatment. (Photograph courtesy of OrthoCAD)



Fig. 12.21 Patient RA. The lower right lateral incisor is lingually placed and excluded from the arch.

correct position. For unerupted teeth, position the brackets on the adjacent teeth so as to move the roots of these teeth away from the unerupted tooth so as to facilitate its eruption. The forces generated by self-ligating brackets are not modified or absorbed by elastomeric ligatures and more direct transmission of the archwire energy to the archwire takes place²⁵. Moreover, the full entrapment of the archwire by the bracket can lead to higher moments than occur with conventional ligation¹⁴. Very gentle forces are therefore all that are required with self-ligating brackets because of their more efficient utilization of archwire energy.

Space in the arch perimeter can be made with open nickel–titanium coil spring which should be activated no more than a single bracket width where a single tooth is completely excluded from the arch; in practice this is approximately 3–4 mm greater than the available space. This is demonstrated in Figs. 12.21, 12.22, 12.23 and 12.24. If a lower incisor is completely excluded from the arch, and the adjacent teeth are in contact, then one of the adjacent teeth should be left temporarily unbracketed but tacked to its adjacent tooth with a malleable stainless steel (Reliance Bond-A-Braid (Reliance Orthodontic Products, PO Box 678, Itasca, IL 60143, USA)) or glass-fibre braid (EverStick Ortho (Stick Tech Ltd, PO Box 114, FIN-20521 Turku, Finland)).

Similar over-corrections should be made to bracket position when root positioning is particularly important, such as in preparing space for an implant.



Fig. 12.22 Patient RA. Space is being made for the lower right lateral incisor with the use of open nickel–titanium coils spring activated no more than one bracket width more than the interbracket space.



Fig. 12.23 Patient RA. The lower right lateral incisor is now in the line of the arch but requires labial root torque.

Over-angulating the brackets on the teeth either side of the implant space to ensure the roots do not encroach into the space is recommended. If this results in a less than ideal position of the clinical crowns of the teeth adjacent to the implant space, then this can be corrected in the latter part of treatment.

For larger spans, such as 4 × 2 appliances (known in the Damon System as D-Gainers as they are used to gain space for unerupted canines in the line of the arch), greater activation will be required. This type



Fig. 12.24 Patient RA. The final position of the lower right lateral incisor after 12 months' retention.



Fig. 12.26 Upper occlusal view of D-Gainer. (Photograph courtesy of Dr Alan Bagden)



Fig. 12.25 D-Gainer being used to open space for unerupted canines in the line of the arch. (Photograph courtesy of Dr Alan Bagden)



Fig. 12.27 Treatment complete with both upper canines correctly aligned following use of D-Gainer. (Photograph courtesy of Dr Alan Bagden)

of appliance is shown in Figs. 12.25, 12.26 and 12.27.

The objective is to keep forces low and allow the space to open slowly without placing undue stress on the adjacent periodontal tissues. Tooth angulation is primarily controlled by the angulation built into the bracket prescription; small adjustments to this may be required in the late stages of treatment to optimize tooth position.

Z-axis movement

This is equivalent to Tweed's first-order movement. Pandis *et al.*²⁶ compared the forces applied to the tooth for buccal and lingual movement for conventional ligation and active and passive self-ligating brackets using the Orthodontic Measurement and

Simulation System²⁷ which incorporates two three-dimensional force-moment sensors. They found that for lingual movement, the active self-ligating bracket applied less force to the tooth because of the resilience of the active clip whereas the passive self-ligating bracket and conventional ligation applied similar forces; there was no difference in applied force when the tooth was moved in a buccal direction.

Bucco-lingual or labio-palatal movement of teeth is relatively simple in cases of mild crowding and frequently tooth alignment can be achieved with no conscious effort to create space by increasing arch



Fig. 12.28 A thick traction hook has been placed on the upper left lateral incisor at the start of treatment as there is not sufficient space to place a bracket in an ideal position on the tooth. The broader traction hook starts to achieve some limited rotational control as can be seen by the wire deflection. The brackets used are Carrière (Class One Orthodontics, 5064 – 50th Street, Lubbock, TX 79414) passive self-ligating brackets.

perimeter. In these cases, it is normal to be able to place brackets on each tooth in their ideal location. Where more severe crowding is present, and the displaced tooth is at some distance from the arch, a thin traction hook should be placed on the displaced tooth which is then attached to the archwire with an elastic thread as demonstrated in Fig. 12.22. Where there is insufficient room to place a full-sized bracket on a displaced or rotated tooth, a traction hook should be placed instead; if space permits, a broad traction hook is preferred as this will give more rotational control once it is possible to put the archwire through the lumen of the traction hook as shown in Fig. 12.28.

Even in mild malocclusions, however, a tooth is occasionally sufficiently rotated to make ideal bracket placement impossible; in these cases a broad traction hook should be placed for a visit or two until a self-ligating bracket can be placed in an ideal location. A thin traction hook has virtually no rotational control and is of little value in this circumstance. The archwire passes through the lumen of the traction hook on the rotated tooth. The elastomeric chain is then stretched by one or two links and attached to an anchor tooth further round the arch which has a bracketed tooth either side of it;



Fig. 12.29 Patient RO at the start of treatment. The lower left central incisor is rotated.



Fig. 12.30 Patient RO at second treatment visit (8 weeks of treatment). A traction hook has been placed on the lower left central incisor; power chain has been looped round the archwire mesial to the lower left central incisor and run back, without engaging other brackets, to the hook on the first molar.

this is necessary to prevent excessive rotation of the anchor tooth. The principles of this technique are shown in Figs. 12.29, 12.30 and 12.31.

The elastomeric chain can either be placed on the archwire before placement or once the wire is in place. To achieve the latter objective, push a pair of elastomeric ligature clips through the end link of the elastomeric chain; pass the free end of the chain behind the archwire and grasp the free end with the clips pulling the chain through the end link of the chain that the clips went through.



Fig. 12.31 Patient RO. Fourth treatment visit (20 weeks of treatment). Alignment of the lower arch achieved. Note the rotation of the lower left first molar; it would have been better to have run the powerchain back to the first or second bicuspid where the tooth would have been supported by a bracket or tube either side to lessen the effects on the anchor tooth.

The rotated tooth normally corrects its position in a single visit. Occasionally, the couple can be enhanced by the placement of lingual buttons and lingual elastomeric traction. Once the rotation is corrected, a self-ligating bracket can be placed in its ideal location on the tooth surface.

Where rotated teeth are significantly displaced from the arch, it is worth considering off-setting the traction hook so as to provide a moment to derotate the tooth as it is moved towards the line of the arch as shown in Figs. 12.32, 12.33 and 12.34. Once again, as the tooth gets close to the line of the arch, the archwire can be placed through the lumen of the traction hook.

Y-axis movement

This corresponds to vertical movement of individual teeth in its translatable form. Pandis *et al.*²⁶ have also looked at this dimension and shown that both active and passive self-ligating brackets generate 20% less force than conventional ligation whether the tooth is being extruded or intruded.

Mild malocclusions rarely pose a problem; leveling is accomplished by balance intrusion and extrusion of individual teeth. When there is greater vertical discrepancy between individual teeth, the balance of



Fig. 12.32 Patient GB. First visit (0 weeks of treatment). The upper left canine was ectopic and palatal and was uncovered using an open exposure. The traction hook has been offset to facilitate rotation of the canine as it moves towards the line of the arch.



Fig. 12.33 Patient GB. Second visit (8 weeks of treatment). Some derotation and buccal movement of the canine has taken place; the archwire can now be placed through the lumen of the traction hook.

intrusion and extrusion of individual teeth can be upset and teeth previously in occlusion can be moved out of occlusion because of the anchorage requirements of a single tooth. Non-pathological examples of this are high, buccally placed canines and pathological examples are unerupted canines and incisors. Caution should be used before engaging high buccally placed canines on a light continuous archwire; etiologically, these teeth are positioned like this



Fig. 12.34 Patient GB. Third visit (16 weeks of treatment). The ectopic canine is now in the line of the arch and approximately aligned; a full sized passive self-ligation bracket (Damon2) has been placed to allow the continuation of treatment.

because there is insufficient space in the line of the arch. The first objective is to make adequate space in the arch perimeter in which case these teeth frequently erupt into a more satisfactory position. Once they have erupted closer to the occlusal plane, they can be bracketed in the normal manner. Self-ligating brackets are ideal for aligning these teeth as considerable relative movement needs to take place between the archwire and the brackets on the adjacent teeth as the tooth moves towards the occlusal level. If necessary, the adjacent teeth can be supported in occlusion by the use of triangular elastics to the opposite arch either side of the displaced tooth which stabilizes the adjacent teeth while allowing free movement of the displaced tooth.

Where pathology exists, or has existed, the situation is different partly because the displaced tooth will frequently be unerupted and may have been subject to a closed exposure technique with a gold chain attached to it. These teeth often exhibit movement and then cease to move; this is attributed to ankylosis. It is suggested that ankylosis is a rare sequela once a tooth has started to move. It is more likely that the tooth becomes impacted on cortical bone which turns over so slowly that tooth movement appears to have ceased. This is not ankylosis but rather a temporary cessation of tooth movement due to impaction into cortical bone. Removal of cortical bone from around the crown of the unerupted

tooth is frequently sufficient to ensure its continued eruption.

Torque is Tweed's third-order tooth movement and represents rotation about the y-axis. This is one of the most difficult tooth movements for edgewise appliances to produce because of the mechanical disadvantage involved – the relatively small forces generated by a small rectangular wire on its edge attempting to produce movement some distance from the center of resistance of the object it is trying to move. It is sensible to select the appropriate selective torque and so upper incisors that require significant root torque should have high torque brackets. Badawi *et al.*²⁸ have investigated torque expression with active and passive self-ligating brackets and have concluded that there is a difference in the angle of engagement between active and passive self-ligating brackets. Active self-ligating brackets started to express torque at 7.5° (SPEED and In-Ovation) of archwire rotation and passive self-ligating brackets (Damon2 and SmartClip) at 15°. The authors suggest that the active clip reduces the play between the archwire and the slot thus increasing archwire expression. The actual slot height was not measured in this study and this may have affected the effectiveness of torque transmission²⁹. Nevertheless, the balance of evidence at present is that active self-ligating brackets are more effective at transmitting torque than passive self-ligating brackets in the laboratory setting. One clinical embodiment of this finding is the Hero System³, a differential friction system, which uses active self-ligating brackets (Time 2) in the anterior segments and passive ligation in the posterior segments; this latter feature is achieved by using upper premolar and molar tubes and lower second premolar and molar tubes. Clinically, the effectiveness of passive self-ligating brackets in achieving adequate inclination of the upper incisors seems to be similar to conventionally ligated brackets³⁰.

For instanding palatal or lingual teeth, the commonly advocated counter-measure of inverting the bracket is not recommended. This counter-measure rarely gets the root in the correct position and, for self-ligating brackets, bracket inversion results in the bracket gate or slide working in the wrong direction. Alternative solutions are the use of torquing auxiliaries either to produce palatal lingual root torque or as reverse torquing auxiliaries to produce labial root torque. Torquing auxiliaries may be an effective



Fig. 12.35 An anterior root torquing (ART) auxiliary used to obtain additional torque in the upper labial segment.

way for providing additional torque in both upper and lower arches and can be used with all bracket systems (Fig. 12.35). For individual teeth, it is more practical to place torque in a titanium–molybdenum or stainless steel archwire using Rose pliers or Tweed 442 pliers.

Movement of multiple teeth

The movement of multiple teeth requires different mechanics to those of individual teeth.

Along the arch perimeter

Space opening

Space opening for individual teeth has already been discussed. The use of self-ligating brackets may permit the use of the musculature of the lips to provide anchorage to assist in the distal movement of buccal segments. This is, and is not, an unusual concept in orthodontics. The Frankel appliance and lip bumpers have successfully used oral musculature to influence tooth position but, while they are respected orthodontic technologies, they have not established themselves as mainstream orthodontic modalities for reasons of fragility, unpredictability of treatment response and doubts about the stability of the changes produced. The suggestion that fixed appliances might permit oral musculature to influence tooth position is a claim made for the Damon System appliance. The force exerted on the labial surfaces of the teeth in the midline has been shown to be 740 N/m^2 and in the right canine area as

450 N/m^2 by Shellhart *et al.*³¹; these figures were lower than those described by Soo and Moore³². Badawi²⁵ at the University of Alberta has developed an orthodontic simulator (OSIM)³³ using 14 three-dimensional force moment sensors (one for each tooth) to simulate and measure the forces and moments applied to displaced teeth and the resultant forces applied to other teeth in the arch. This has shown that in the alignment of high buccal canines, passive self-ligating brackets generate anteriorly directed forces on the incisors that are below the forces determined by Shellhart *et al.*; conventionally ligated brackets produced anteriorly directed forces greater than the resting lip pressures determined by Shellhart *et al.* Active self-ligating brackets produce forces greater than the passive self-ligating brackets but significantly less than the conventionally ligated appliances. This means that the teeth to which self-ligating appliances are attached, and particularly passive self-ligating appliances, might be able to use the perioral musculature to provide some anchorage for tooth movement in some cases. The reason for this is the lack of friction between archwire and bracket which allows the archwire to slide easily through the brackets posteriorly and thus does not generate anteriorly directed forces which exceed lip pressure, thus allowing the lips to provide anchorage. However, a final judgement on this hypothesis must await published results in a peer-reviewed journal.

The use of a 4×2 (or D-gainer) to open space for upper canines frequently requires anterior movement of the upper anterior teeth to obtain a normal incisor relationship. This may happen spontaneously, but if this is difficult to achieve, a lower 4×2 with light class II traction can be used to alter the balance of forces to encourage anterior movement of the upper teeth. No tooth movement in orthodontics occurs in only one dimension and this type of tooth movement will result in a reduction of the existing overbite due to incisor proclination and extrusion of the upper molars.

Space closure

In the language of Toyota, space closure following extraction is *muda*³⁴ or waste, in that it adds no value to the process of orthodontic treatment; it simply corrects a defect made earlier in the treatment – the overprovision of space within the dental arch by extraction. This view of extraction may be

slightly unusual but it merits reflection. Self-ligating brackets, because of their full bracket engagement, ensure that the unwanted consequences of space closure, such a rotation into the extraction space, do not occur. While it might be thought space closure would be more rapid with self-ligating brackets because of their lower resistance to sliding friction, the only additional friction for conventionally ligated brackets is normally a single elastomeric ligature per side on a premolar tooth and this may be insufficient to generate much difference between the two methodologies. The differences in rate of space closure between the two systems are unproven but require further investigation.

In the self-ligating system, it is suggested that space is closed using nickel–titanium coil springs and that these may be attached anteriorly to archwire posts and posteriorly, the fitting on the end of the coil is slipped over the terminal end of the archwire rather than over the molar tube hook.

Where a power chain is used to close space, placing it under the archwire is slightly less convenient but reduces friction between archwire and power chain. Therefore, where there are significant amounts of space to close, the power chain should be placed under the archwire; where the amount of space to be closed is relatively small or where the power chain is only being used to prevent space opening, the power chain can be placed over the archwire as it can then be changed without removing the archwire.

Centerline correction

Minor centerline correction is most easily accomplished by the use of cross-elastics. The placement of a Kobayashi ligature or the use of a drop-in hook on a lower central incisor bracket can be used as a guide to make the vector of an anterior cross-elastic more comfortable.

Antero-posterior movement – class II correction

The preferred method of correction for moderate to severe class II malocclusions that are amenable to orthodontic treatment in the mixed dentition is the functional appliance. The type of functional appliance will vary according to operator preference – removable two piece (Clark Twin Block), removable one piece or fixed functional appliance (Herbst).

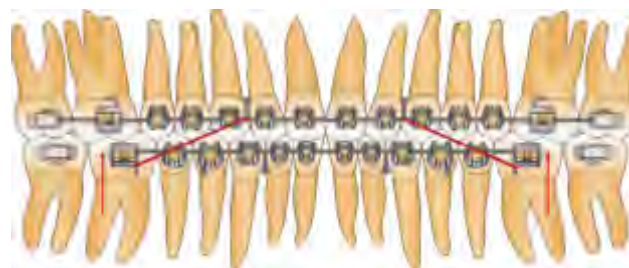


Fig. 12.36 When using class II elastics, the archwire is terminated distal to the lower first molars.



Fig. 12.37 Fixed class II corrector (TP Flip-Lock Herbst) attached to the archwire between the upper first and second molars and the lower cuspid/first bicuspid.

Mild to moderate class II malocclusions can be corrected with class II elastics. Class II elastics should be used 24 hours a day and should be 3/8" elastics; class II correction seems to occur more quickly if the archwire is terminated distal to the mandibular molar as shown in Fig. 12.36 but further evidence is required to demonstrate the efficacy or otherwise of this technique.

More severe malocclusions can be corrected with a fixed class II corrector, such as TP Flip-Lock Herbst attached to the archwire (Fig. 12.37). The TP Flip-Lock Herbst axles are soldered to 0.022" × 0.028" Inconel tubing with a 2 mm tube offset; this allows the axle to be placed between the brackets or tubes with no play. These are placed between the upper first and second molars and between the lower canines and first bicuspid. The use of self-ligating upper first molar tubes facilitates the placement of the axle tube between the upper first and second molars; the upper archwire should be cut with an outward bevel to facilitate engagement of the archwire in the upper second molar tube. The Flip-Lock

Herbst cylinders and pistons frequently do not need to be shortened in non-extraction cases when the axles are positioned as suggested. Each buccal segment should be ligated from the second molar tube to the archwire hook to prevent space opening up in the buccal segments. Preposted archwires should be used as these are the most effective way to counteract the swiveling forces which are generated due to friction between the tubes on the axles and the archwire. As with all functional appliances, the objective is to obtain a class I canine relationship. Once this is obtained, the Herbst should maintain the correction passively for 6 months to allow the bony change in the condyle to stabilize.

Antero-posterior movement – class III correction

Class III traction is invariably produced using intermaxillary elastic traction and this is demonstrated in Fig. 12.38. The same principles as outlined above should be used:

- 0.019" $\times$ 0.025" stainless steel preposted archwires should be used
- The archwire should be terminated distal to the upper first molars

Transverse movement – arch expansion

Arch expansion in the transverse direction is traditionally carried out using some form of expander. It is debatable whether the decision as to what expander is used is based on scientific logic or custom and personal preference, but the techniques fall into two categories. Rapid maxillary expansion uses a jack screw which is turned daily or twice daily to obtain splitting of the mid-palatine suture with the aim of getting more bodily movement, and less

tipping of the buccal segments as expansion occurs. Slow maxillary expansion commonly uses a spring device in the palate, such as a quad-helix, to produce transverse expansion of the upper arch primarily by buccal tipping of the molars and premolars.

The differential diagnosis of posterior crossbite is important and many posterior crossbites only involve the first molars and premolars while the second molars remain in a normal relationship. While not the only factor that needs to be taken into account, the increased ease of incorporating second molars into fixed appliances mean this type of crossbite is perhaps more amenable to correction with archwires only.

The Damon System appliance utilizes a different technique which is claimed to significantly reduce the need for auxiliary appliance expanders. The broad Damon archform, combined with the low friction of self-ligating brackets, typically produces significant expansion in the premolar and molar regions. This characteristic can be used to correct posterior crossbites. In some cases, the posterior crossbite corrects spontaneously. However, more reliable crossbite correction occurs if bilateral cross-elastics are started from the first treatment visit. In some cases, expanded stainless steel archwires are required in the upper arch to initiate and complete crossbite correction. 0.016" $\times$ 0.025" stainless steel archwires permit more tipping in the buccal segments than 0.019" $\times$ 0.025" wires in particularly refractory cases. Changes in intermolar and inter-premolar width, particularly in the upper arch, can be up to 10 mm of expansion but more commonly approximately 6 mm. These are similar to the amounts of expansion achieved by McNally *et al.*³⁵ in their comparison of the effectiveness of buccal expansion arches and quadhelices. Mikulencak³⁶ conducted a retrospective study to compare tipping produced by rapid maxillary expansion (in previously published studies) with the tipping produced by the Damon System appliance and found no difference in the amount of molar tipping associated with the increase in arch width between the two methodologies. An inverse relationship was found between pre-treatment molar arch width and change in molar angulation with the Damon system.

Why this is possible is uncertain; it may be in part due to the reduced friction between archwire and bracket and the broad archform of the Damon System; if so, this may be more apparent with passive

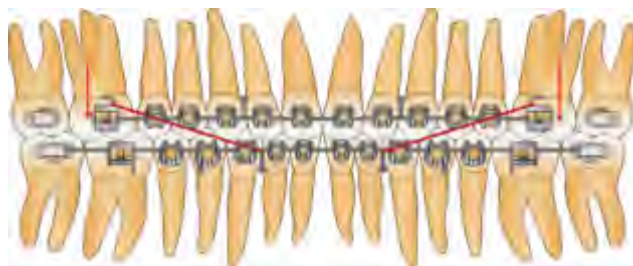


Fig. 12.38 When using class III elastics, the archwire is terminated distal to the lower first molars.

self-ligating bracket systems. Hypotheses about the amount of expansion that can be obtained with self-ligating brackets and how this differs from more conventional expansion techniques require further investigation.

Transverse movement – arch contraction

Arch contraction may be required in the presence of scissor bites. Correction of this type of malocclusion requires disclusion, expansion of the narrower arch and, if possible, contraction of the wider arch. Arch contraction requires space in the arch and if the arch is not already spaced, then extractions will be required.

Vertical movement – overbite reduction

While much of orthodontics is based on science, much of it is pragmatic. The non-extraction treatment of class II division II malocclusions, in which the principal problem is usually overbite reduction, is an example. Extractions make management of the overbite extremely difficult as the mechanics required to close any residual extraction space result in an increase in overbite which requires compensatory mechanics to counteract; frequently, these countermeasures have proved inadequate. Non-extraction treatment facilitates overbite reduction by incisor proclination (Figs. 12.39 and 12.40) and so for most cases, orthodontists prefer to treat class II division II malocclusions without extractions as it makes treatment more predictable and successful.



Fig. 12.39 Patient RA. Center occlusion at the start of treatment with increased overbite.

Vertical movement – closure of anterior open bite

Anterior open bites are difficult to manage. It is important to try to understand the etiology as well as planning the treatment mechanics necessary to close it. In the absence of facial disproportion, anterior open bites are often caused by a digit-sucking habit or tongue posture problem. While digit-sucking habits are relatively easy to manage, tongue posture problems are more difficult to diagnose and quantify. The use of tongue cribs³⁷ can be an effective way of changing tongue posture (Figs. 12.41 and 12.42). Although in this example, the tongue crib was placed in the mandible, these are best tolerated when fitted in the maxilla^{38,39}, either to a palatal arch



Fig. 12.40 Patient RA. Center occlusion 12 months after the end of treatment with normal overbite; overbite correction was facilitated by the non-extraction treatment.



Fig. 12.41 Patient KF. Start of treatment with anterior open bite and tongue resting between incisors.



Fig. 12.42 Patient KF. 18 months after cessation of tongue spurs showing normal overbite maintained.

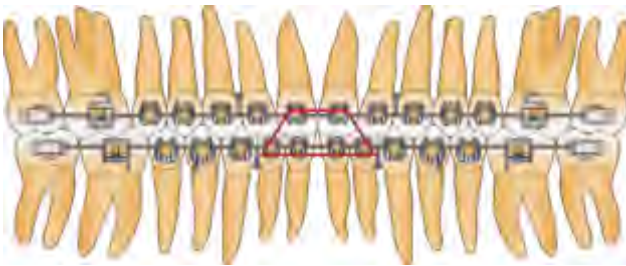


Fig. 12.43 Anterior trapezoidal elastic to close small anterior open bites. Note that because the tie wings of self-ligating brackets do not have to accommodate elastomeric ligatures, it is often possible to use the tie wings to retain the elastics.

or by bonding habit preventers to individual teeth using a Mini-Mold.

If anterior open bites do not respond to the measures described above, then extractions should be considered. Whereas increased overbites respond well to non-extraction treatment, anterior open bites conversely frequently require extractions to increase the overbite and therefore close the anterior open bite. The choice of extraction will depend on the clinical circumstances and the operator's philosophy. While premolar extractions will probably have a more direct effect on the overbite, some orthodontists may prefer the extraction of terminal molars⁴⁰.

Finalization of the overbite can be achieved by using an anterior trapezoidal elastic as shown in Fig. 12.43.

Vertical movement – developing interdigitation

Ideally, bracket positioning will have been sufficiently good for interdigitation to develop in the

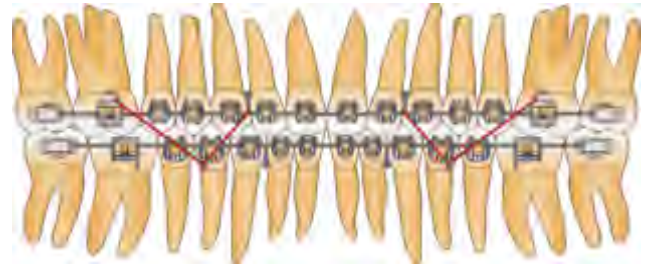


Fig. 12.44 Posterior V elastics used to develop interdigitation and finalize the occlusion. These again can be placed around the tie wings.

final stages of treatment. Where necessary, posterior V elastics, as shown in Fig. 12.44 can be used to ensure good contact in the buccal segments.

RETENTION

Robert Little's work⁴¹ on the Seattle studies have made it clear that in order to obtain an optimal orthodontic result, the active treatment should be carried out as expertly as possible and that the result then requires to be retained permanently in order to ensure maintenance of that result. Despite the hope that some way would be found to carry out orthodontic treatment such that a stable result would be maintained indefinitely without the need for continued retention, such a search has proved elusive and the goal is probably unrealistic. Continued low-level maintenance is currently required to ensure that the result obtained at the end of active treatment is maintained. Retention should be considered under both retaining the alignment of teeth and the retention of intermaxillary relationships.

Retaining alignment of teeth

Retaining the alignment of teeth is best done through the use of both fixed and removable retainers. The combination of both types provides some resiliency should one method fail.

Fixed retainers are used from lower canine to canine and from upper lateral incisor to lateral incisor. For the lower canine retainer, the method of construction and placement is based on that of Rogers and Andrews⁴². The following technique is recommended:

- Ensure a clean, dry bonding field
- Sandblast the lingual surfaces of the lower canines using a microetcher. The retainer is only bonded to the lingual surfaces of the lower canines
- The retainer is made out of 0.025" (0.6 mm) single strand stainless steel wire with flattened, contoured and sandblasted ends
- Cover the ends of the retainer with at least 0.25 mm of flowable composite and contour as necessary

Bonding the lower canine to canine retainer to the canines only makes it more reliable as there are only two bonds to fail instead of six, it is easier for the patient to notice when a bond failure has taken place, it allows the lower incisors some scope for movement but is probably a less positive method of maintaining incisor alignment than a multistrand wire bonded to the four lower incisors and two canines. However, these retainers are not without complication⁴³ and this latter point is compensated for by the concurrent use of the lower removable retainer which maintains lower incisor alignment.

The upper lateral incisor to lateral incisor fixed retainer is made from a flat, dead soft eight-braid stainless steel wire such as 0.016" × 0.025" Bond-A-Braid. It is important that the palatally placed retainer is completely clear of the occlusion, yet covered by an adequate thickness of adhesive, to prevent premature failure.

The preferred type of removable retainer is a vacuum- or pressure-formed retainer. These have been shown to be marginally more effective in retaining tooth alignment than Hawley type retainers^{44,45}. Furthermore, there is early evidence⁴⁶ that part-time night-only wear (greater than 8 hours) may be as effective as fulltime wear of vacuum-/pressure-formed retainers. The recommended protocol for removable retainer wear is therefore night-time only wear.

Retention of intermaxillary relationships

Conventional retention maintains alignment within the arches rather than intermaxillary relationships. Flanges can be added to vacuum-/pressure-formed retainers to maintain crossbite correction.

The Damon splint (Fig. 12.45) is used in adults to maintain intermaxillary correction and ensure the long-term control of muscular balance and habit.



Fig. 12.45 Damon splint.

This is recommended by Damon⁵ in the following circumstances:

- Herbst appliance cases
- Class II or class III cases corrected with elastics
- Lateral tongue thrust cases
- Severe posterior crossbite cases
- Temporomandibular joint dysfunction cases
- Some sleep apnea cases

Detailed instructions on the construction of the Damon splint retainer are given by Damon⁵.

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